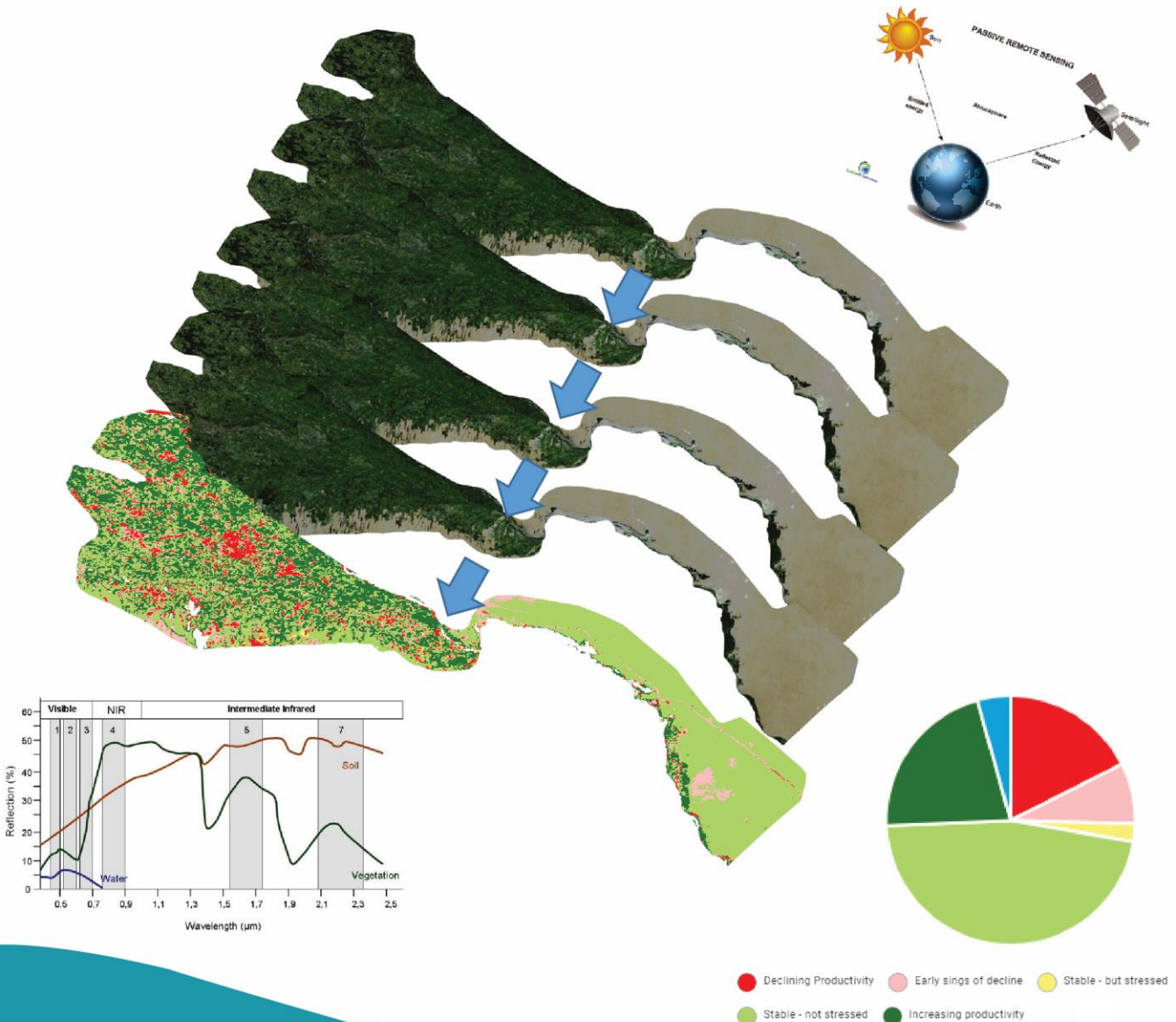


*Ecologically oriented regional development in the Aral Sea region program
Increasing water use efficiency in the Aral Sea Region*

Geodatabase and Atlas: Khorezm province, Uzbekistan

*Zafar Gafurov, Sarvarbek Eltazarov, Tulkun Yuldashev,
Kakhramon Djumaboev, Sherzod Zaitov and Shavkat Kenjabaev*



About GIZ

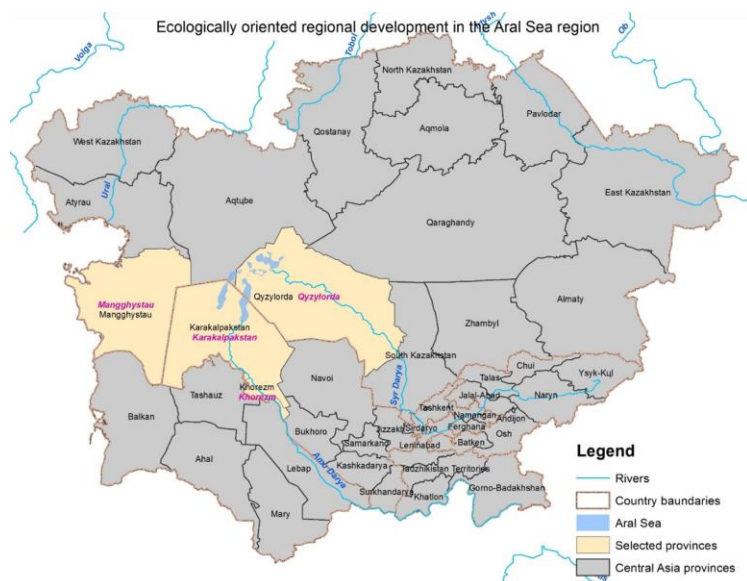
The German Society for International Cooperation (GIZ), as a service provider in the field of international cooperation for sustainable development and international education work, is dedicated to shaping a future worth living around the world. Having over 50 years of experience in a wide variety of areas, including economic development and employment promotion, energy and the environment, and peace and security, GIZ provides tailor-made, cost-efficient and effective services for sustainable development. GIZ has two registered offices in Germany, one in Bonn and one in Eschborn, near Frankfurt am Main. GIZ also operates from about 90 offices around the globe, some of which shared with other German development organisations.


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The International Water Management Institute (IWMI) is an international, research-for-development organization that works with governments, policymakers, farmers, civil society, water managers, development partners and businesses to solve water problems and scale up solutions. Through partnership, IWMI combines research on the sustainable use of water and land resources, knowledge services and products with capacity strengthening, dialogue and policy analysis to support implementation of water management solutions for agriculture, ecosystems, climate change and inclusive economic growth. Headquartered in Colombo, Sri Lanka, IWMI is a Research Center of CGIAR with offices in 15 countries and a global network of scientists operating in more than 55 countries.

About the “Ecologically oriented regional development in the Aral Sea region program”

Since 2020, the project has been supporting two Central Asian states (Kazakhstan and Uzbekistan) to improve the capacity of organisations and individuals, with the aim of enabling them to make climate-adapted and ecologically oriented investment decisions. For further details about the project, visit: <https://www.giz.de/en/worldwide/93488.html>.



A map of Khorezm province in Uzbekistan, showing the Amu Darya river and various districts. The map is overlaid with a grid and features several labels for districts and cities. The title 'Geodatabase and Atlas: Khorezm province, Uzbekistan' is centered over the map in a large, dark blue font.

Geodatabase and Atlas: Khorezm province, Uzbekistan

*Zafar Gafurov, Sarvarbek Eltazarov, Tulkun Yuldashev,
Kakhramon Djumaboev, Sherzod Zaitov and Shavkat Kenjabaev*

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/ spatial databases / atlases / digital elevation models / satellite imagery / maps / land cover / land use / water resources / water supply / water demand / water-use efficiency / irrigation systems / water authorities / water user associations / irrigation canals / drainage systems / groundwater / soil types / soil density / soil organic carbon / soil water content / soil salinity / sandy soils / clay soils / soil pH / climate change / meteorological stations / pumps / evapotranspiration / precipitation / temperature / winds / geographical information systems / remote sensing / Uzbekistan /

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Geodatabase and Atlas: Khorezm, Uzbekistan is based on data and information generated and collected within the framework of the GIZ Program “Ecologically oriented regional development in the Aral Sea region”. Data were also obtained from published and grey literature as well as spatial analyses carried out using publicly available sources. The authors would like to thank local project partners in Karakalpakstan for their valuable inputs and feedback when preparing the material.



This Geodatabase and Atlas was put together within the framework of activities implemented under the GIZ Program “Ecologically oriented regional development in the Aral Sea region” as part of the project “Increasing water use efficiency in the Aral Sea Region” implemented by the International Water Management Institute (IWMI) in collaboration with GIZ and local partners.



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This project is funded by



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This work was carried out as part of the GIZ funded regional project “Ecologically Oriented Regional Development in the Aral Sea Region” (ECO-ARAL) and commissioned by German Federal Ministry for Economic Cooperation and Development (BMZ)

Geodatabase and Atlas

Importance Geodatabase and Atlas

The information systems aimed at data and information management are becoming increasingly important with reference to the processes of decisions-making and strategic thinking in a newly emergent competitive economy setting. In addition to digital data types utilized in information systems, geospatial data have advanced significantly in recent years. Not only do these data include the geographic location of particular sites on the planet, they also specify their shape and size. Spatial data including digital maps are the core component of a GIS. In order to help decision makers with the planning, design and prioritization of investment plans, these data are materialized in the form of files that are compiled into a single database.

Introduction

This Geodatabase and Atlas was developed by the International Water Management Institute (IWMI) in collaboration with regional partners as part of project activities under the GIZ project “Ecologically oriented regional development in the Aral Sea region”.

Capacity-building of micro-, small- and medium-sized enterprises as well as ministries and state agencies is one of the primary focuses of the project in order to enable their employees to make climate-adaptive and environmentally oriented investment decisions. Modern satellite imagery and technologies is one of the areas that create new opportunities for agricultural, forestry and water sector professionals to improve their skills and expertise in regional spatial planning. For instance, remote sensing techniques can be instrumental in identifying environment or climate-related economic risks or cases of degradation for targeted improvements at an early stage.

Data Accuracy and Reliability

The Atlas was created using open source GIS, remote sensing and other relevant data and information, including databases, maps, research, analyses etc. publicly available from renowned international agencies, research organizations and projects.

Availability and Accessibility

The Atlas can be obtained in digital form for use by external parties. When using the Atlas, the authors and the institute should be credited.

Software Employed

This Atlas and associated maps were created on a computer running Windows 10 Professional using ArcGIS, QGIS and Google Earth Engine. End-users should download the map package that is most appropriate for the version of ArcGIS software they are using. It is important to note, however, that ArcGIS is not the only software that allows the use of the map package and the associated geodatabase.

Aral Sea Basin



The Aral Sea, located in the Turan plain of Central Asia and once the fourth-largest inland sea in the world, has undergone many changes. Two major transboundary rivers, the Amu Darya and the Syr Darya, feed the Aral Sea. Their combined basin boundaries, which largely define the Aral Sea basin, cover a total area of 1.9 million km² (Xenarios et al., 2019) and extend over six countries: Kazakhstan, Turkmenistan, Uzbekistan, Afghanistan, Tajikistan and the Kyrgyz Republic. About 35 million people, two thirds of the combined population of these countries, live in the Aral Sea basin. Before 1960, about 60 billion cubic meters (BCM) (Xenarios et al., 2019) of water reached the sea annually. Today, the inflow of water has declined to 5-20 BCM annually and as a result, the level of water in the Aral Sea has dropped by almost 20 meters (m) and its area shrunk by two-thirds, from 67,000 km² in 1960 to 20,000 km² at present (Xenarios et al., 2019). The table in the following page provides some key features of the Aral Sea basin.

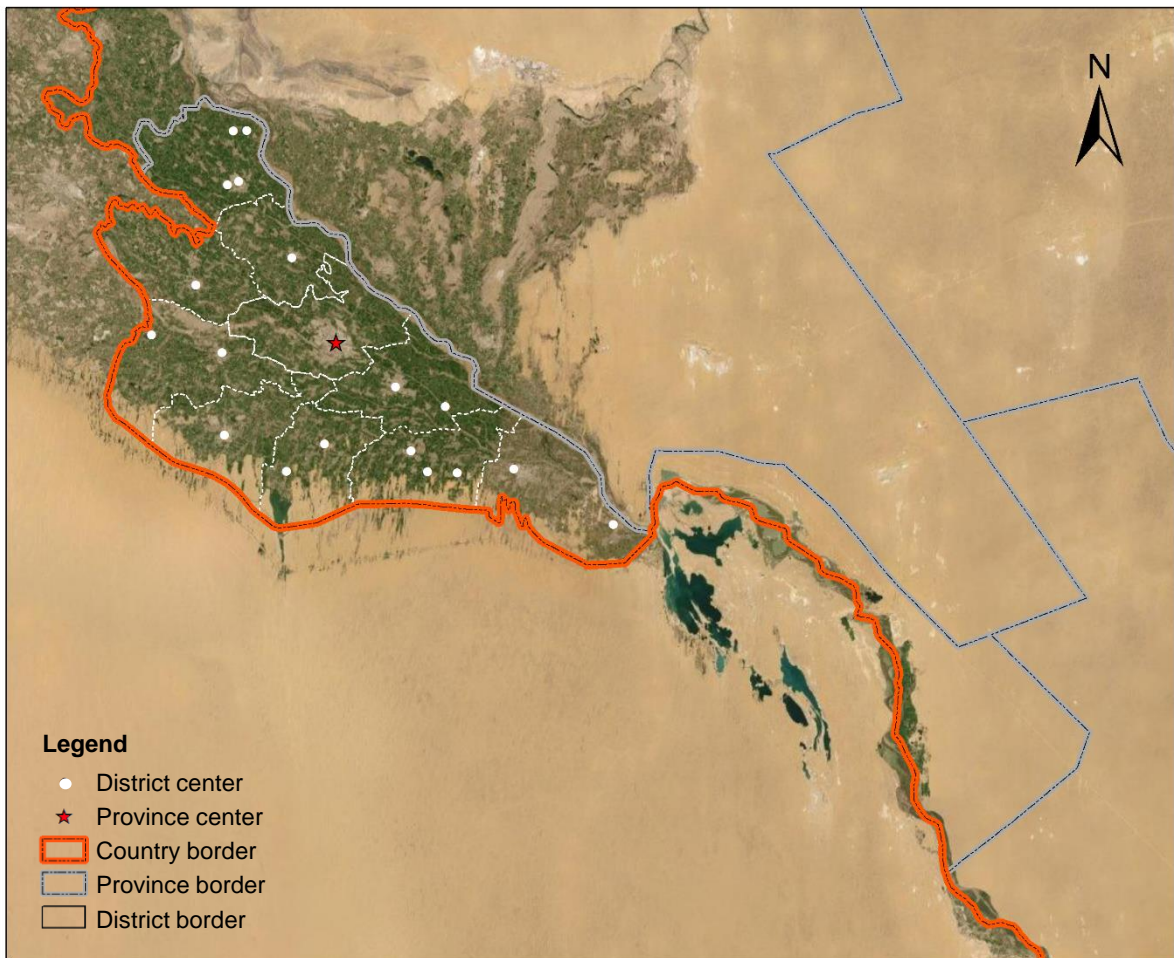
Table Key information on Aral sea basin, surface area and renewable surface water resources by basin countries

Country	Surface area		Renewable surface water resources				
	km ²	% Aral sea basin	% Country area	Amudarya (km ³)	Syrdarya (km ³)	Aral sea basin (km ³)	Aral sea basin (%)
Afghanistan	234800	12	36	6.18		6.18	5.3
Kazakhstan	540000	28	20		4.50	4.50	3.9
Kyrgyzstan	117500	6	59	1.93	27.25	29.18	25.2
Tajikistan	141670	7	99	62.90	0.40	63.30	54.8
Turkmenistan	466600	24	96	0.98		0.98	0.8
Uzbekistan	447400	23	100	4.70	4.84	9.54	8.3
Total	1947970	100.0		76.69	36.99	113.68	98.3
Aral sea basin				78.46	37.14	115.60	100.00

Source: FAO, 2003.

At present, the biggest challenges for the water sector in the region come from weak decision-making capacities of state water management organizations, and un-coordinated and competing interests of different stakeholders and public sectors across all levels of water management. These problems are the root causes resulting in bottlenecks and failures in implementing integrated water management approaches at river basin scale. Current water systems are in transformation, having the attributes of both past and present systems. However, an effective water administration needs to tackle both supply and demand needs, taking care of both the developing economy and the degraded environment (Xenarios et al. 2019).

Satellite view of study area

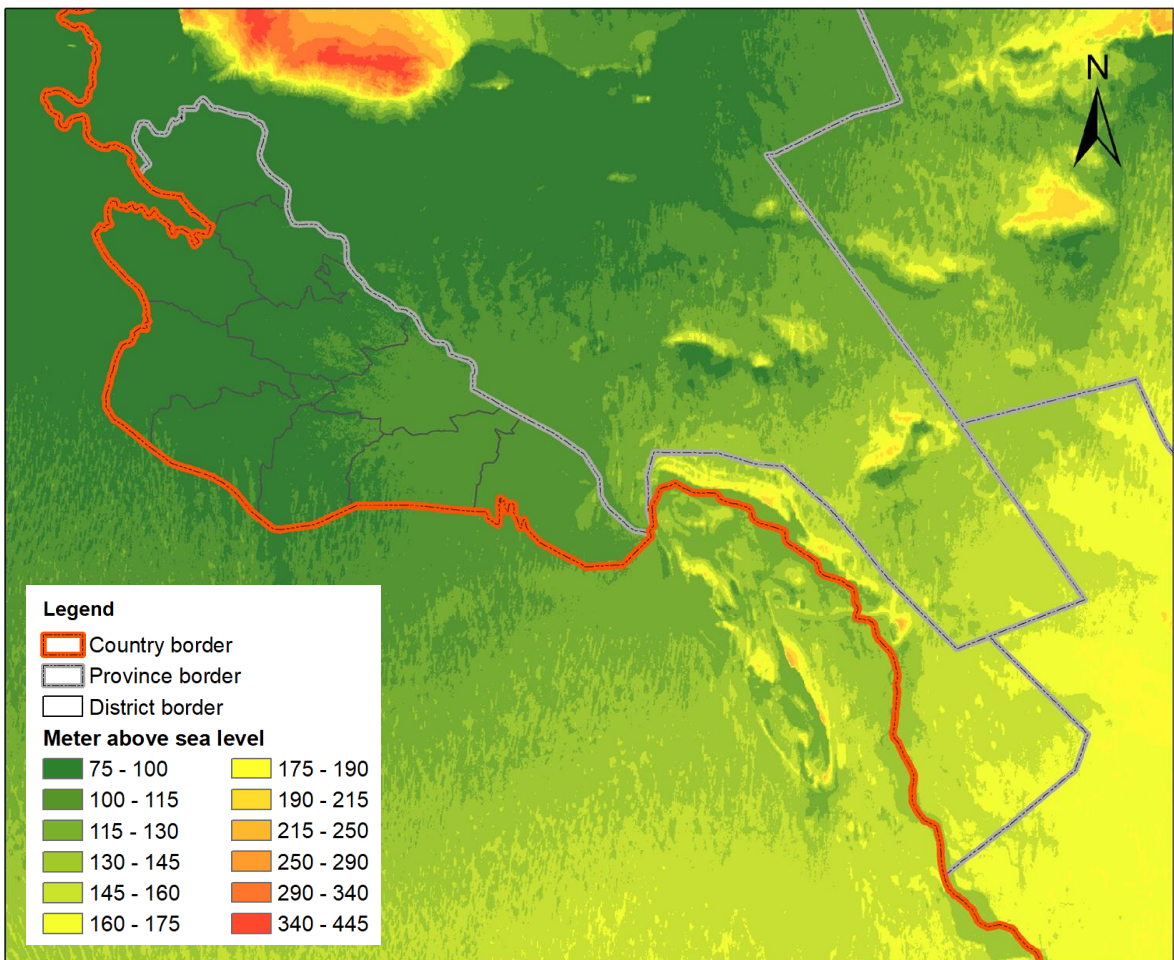


Khorezm province, Uzbekistan

Khorezm is a province of Uzbekistan located in the northwest of the country in the lower delta of the Amu-Darya River. The region borders on Karakalpakstan in the north, Turkmenistan in the south, and Bukhara Region in the south-east.

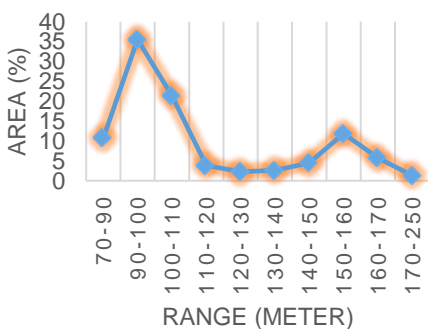
The total area amounts to 6,060 km². The population is estimated at 1804.9 thousand people of which some 67% live in the rural areas (Statistics Agency 2023). The province is divided into 10 administrative districts. The capital city is Urgench (population 140.1 thousand people). Other important towns include Khonqa, Khiva, Shovot, and Pitnak (IPA, 2022).

Digital elevation model



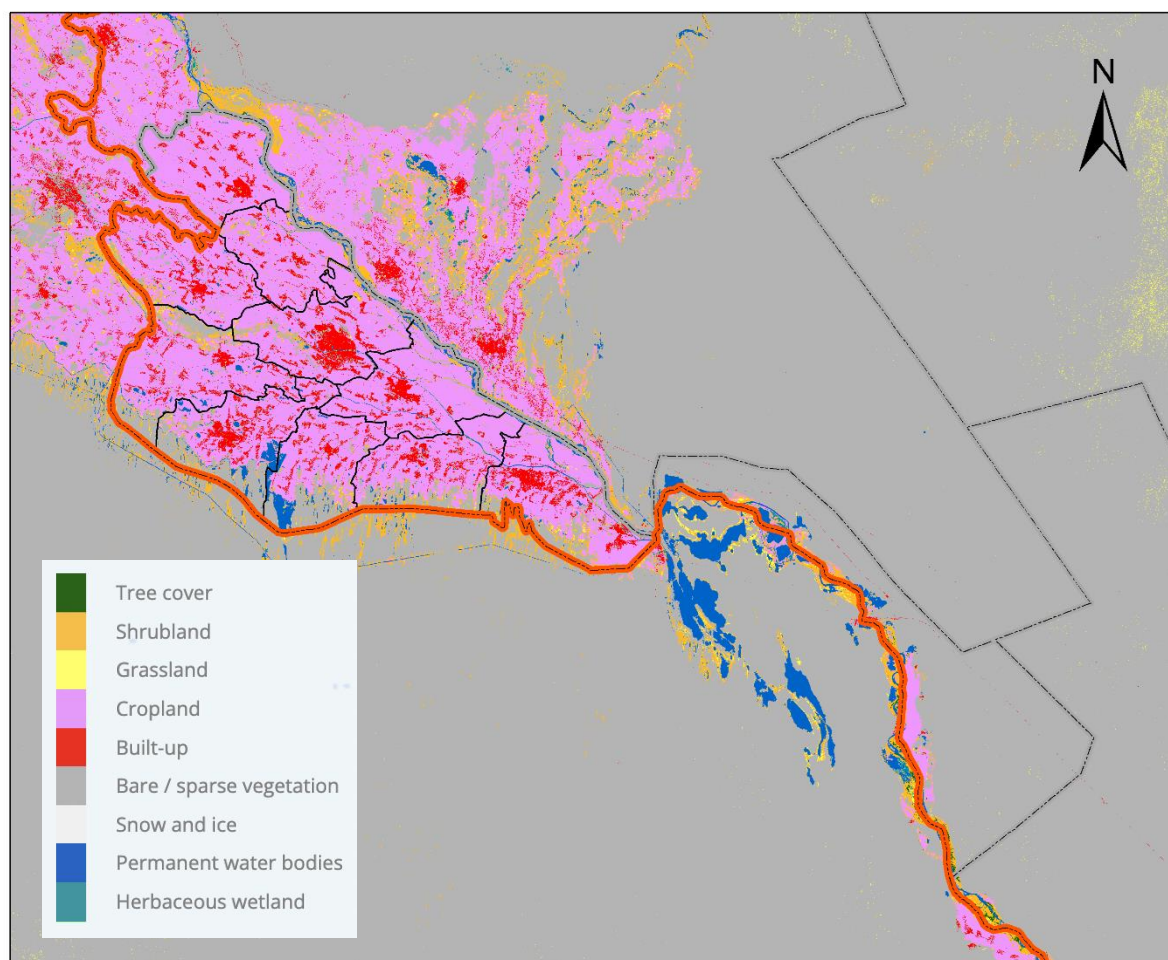
Max Elevation	244 meters
Min Elevation	57 meters
Mean Elevation	113 meters
Mean Slope	2 degrees

The digital elevation model of Khorezm province, Uzbekistan was produced using the publicly available Shuttle Radar Topography Mission (SRTM) digital elevation dataset. SRTM was originally produced to provide consistent, high-quality elevation data at near global scope. This version of the SRTM digital elevation data was processed to fill data voids, and to facilitate its ease of use.



Source: Farr et al. 2007.

Land cover and use map



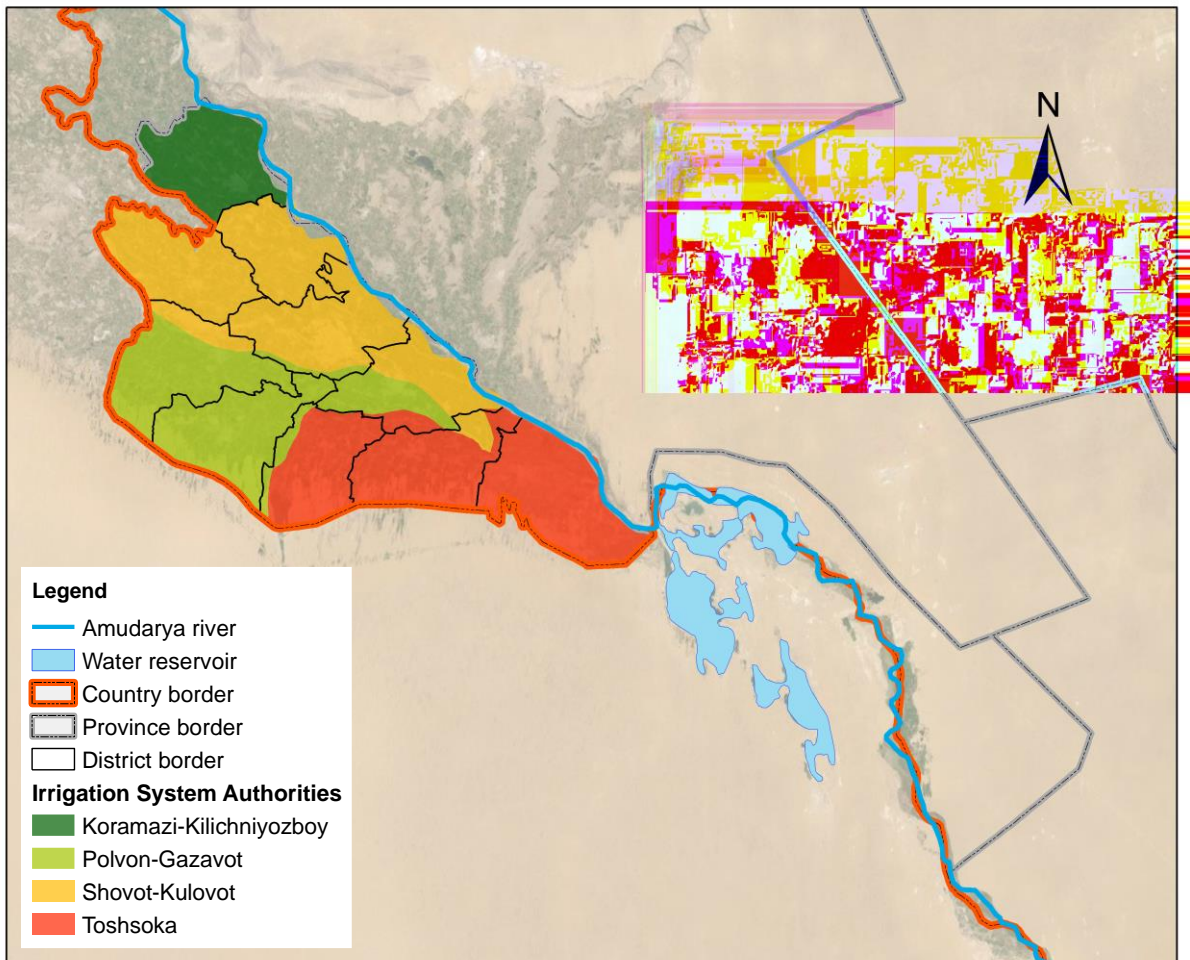
Source: ESA WorldCover product (Zanaga et al. 2021).

Class name	Approx. area(%)
Trees	0.17
Shrubland	4.71
Grassland	0.49
Cropland	48.74
Built-up	6.97
Barren / sparse vegetation	35.38
Open water	3.4
Herbaceous wetland	0.16

The total land area amounts to 608.2 thousand ha, of which irrigated agricultural area is 267.7 thousand hectares, while pasture land for livestock is 109,4 thousand hectares. The area under cotton and winter cereals still occupies the lion's share of all irrigated arable land in the Khorezm Region - 85% (IBRD, 2018). But there is a tendency to diversify crop production, with the land under cotton and wheat gradually decreasing.

The European Space Agency (ESA) WorldCover product provides a global land cover map for 2020 at 10 m resolution based on Sentinel-1 and Sentinel-2 data. The WorldCover product comes with 11 land cover classes and has been generated in the framework of the ESA WorldCover project, part of the 5th Earth Observation Envelope Programme (EOEP-5) of the European Space Agency (Zanaga et al. 2021).

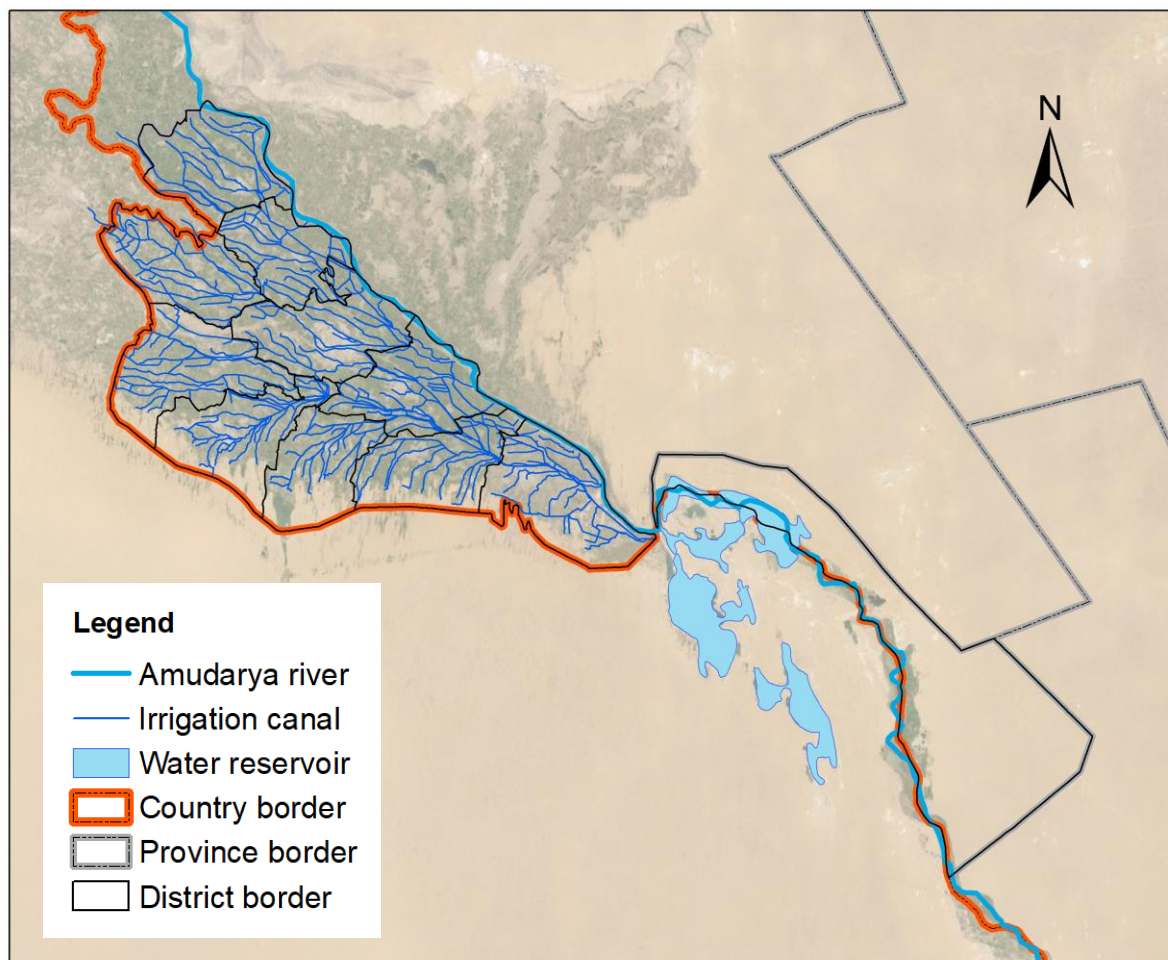
Irrigation system authorities



The institutional framework for managing water resources within Uzbekistan is complex and multi-level. The main governmental body to manage water and implement water sector policies is the Ministry of Water Resources. Further down the ladder, there are a number of operational water management levels to allocate and manage water at cross-basin, basin and sub-basin levels, including handling inter-provincial, provincial, inter-district and district water supplies. Lastly, WCA is a non-state actor that operates at the lowest farmer and rural community level.

Water management at basin/province level in Khorezm is vested with the Amu Darya River's Left Bank Basin Authority (BISA) with four Irrigation System Authorities (ISAs) at sub-basin/inter-district level and 11 irrigation departments (DIDs) at district level under its subordination. The latter make contracts with 11 WCAs before water finally reaches farmers' fields and rural household plots (Djumaboev 2021).

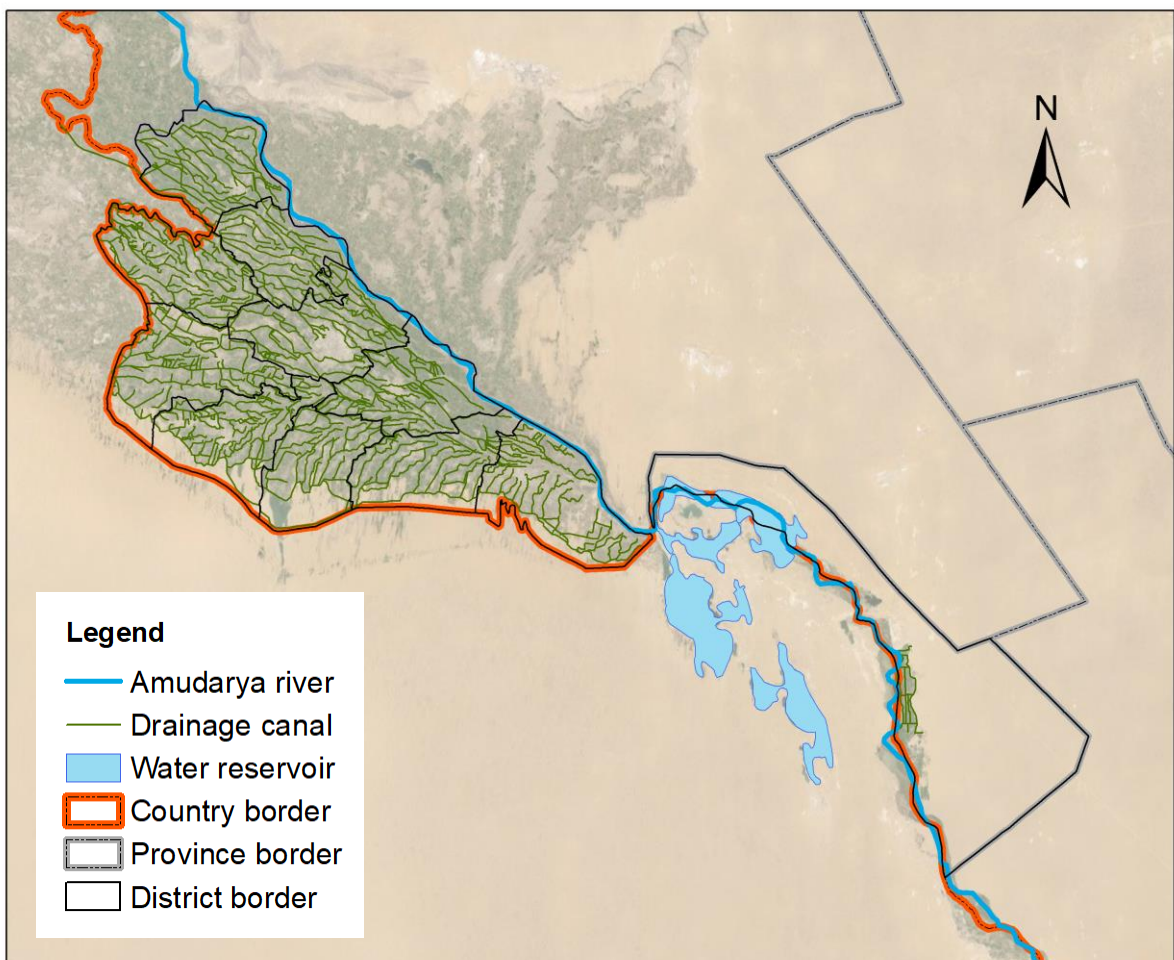
Irrigation canal networks



An extensive and complicated network of irrigation canals coupled with a mesh of drainage facilities in the region mostly originates from the Soviet era, i.e. established in the 1950 – 1970s (Sinnott 1990). Since then, however, the reliability of the system has declined significantly due to lack of maintenance and age (Ibrakhimov et al. 2004), increasing water insecurity (Müller 2006). No upgrade or further development of the system has occurred in Uzbekistan since independence. Due to lack of governmental investment, about 2500 km of canals and drainage collectors in Uzbekistan require reconstruction.

Furthermore, as most canals are not lined, the rate of seepage is very high. As a result, only about 45-50 % of water withdrawals reaches the farmers' fields. At field level there are additional water losses due to furrow irrigation which is the most common method of irrigation in Khorezm.

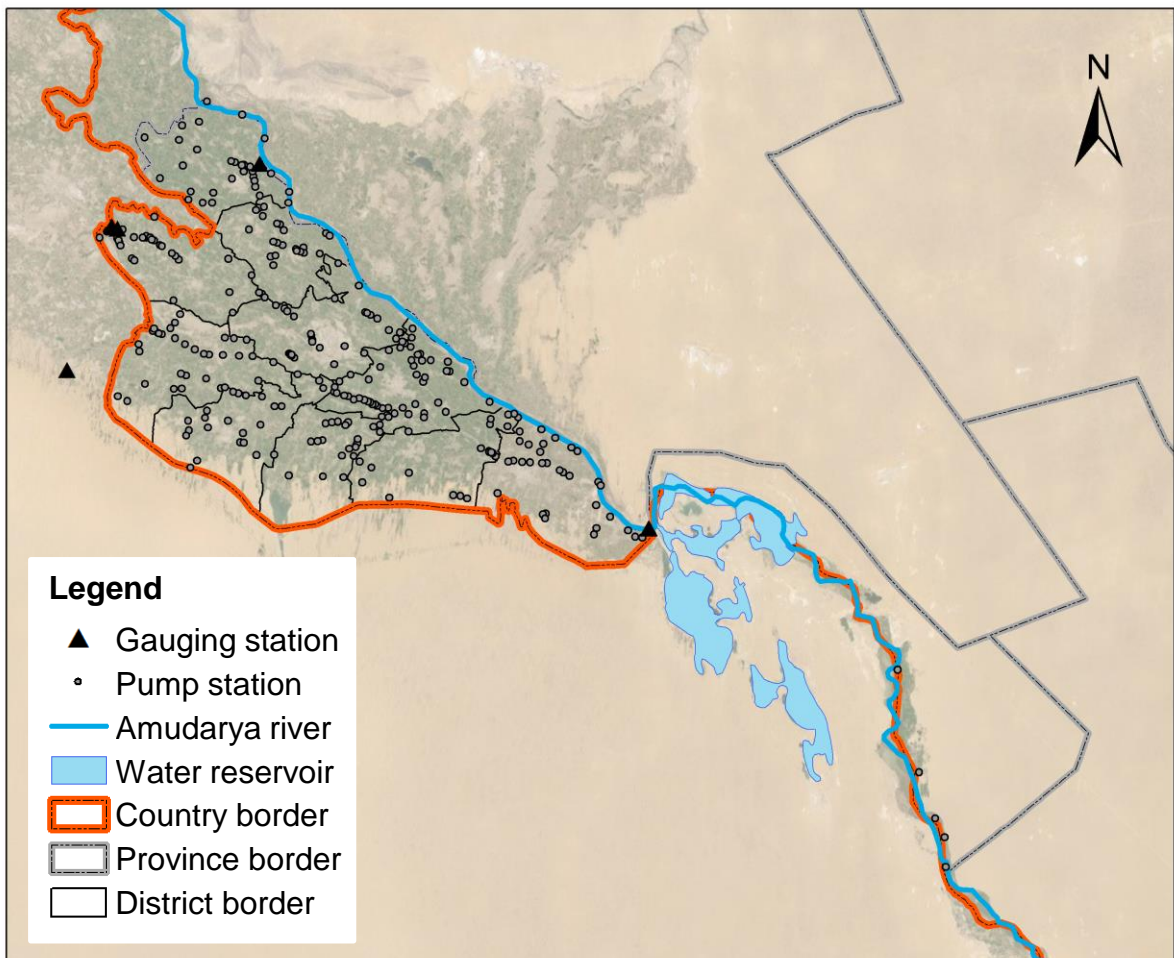
Drainage networks



The per-unit-of-area water supply on the WCA border during the growing season in Khorezm is estimated at 15,997 m³/ha (EBRD and IWMI 2019). Such huge amounts can be explained by underperforming irrigation systems, as a whole, and low levels of organization and skills at the demand-side, such as farmers failing to comply with proper crop irrigation techniques or cropping pattern restrictions, i.e. cultivation of rice.

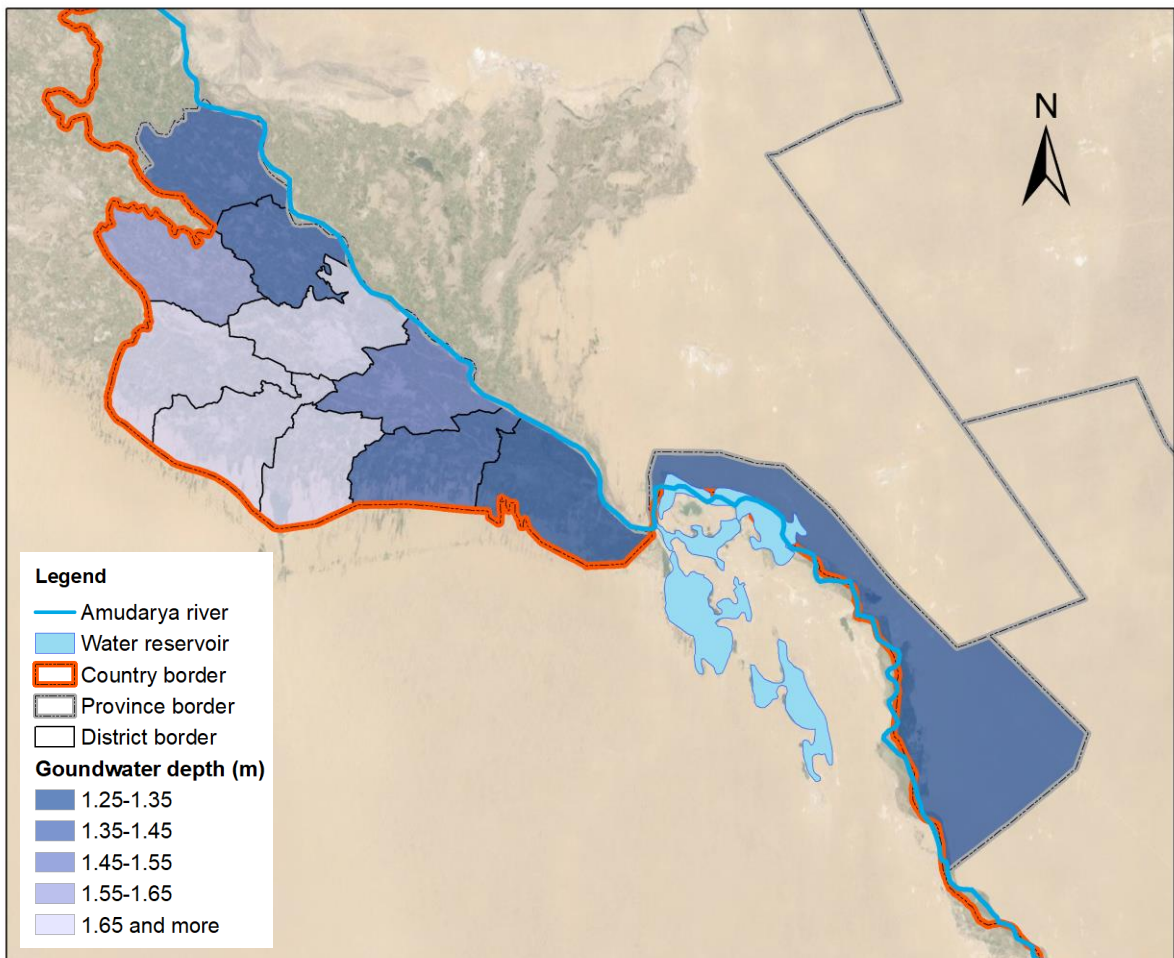
The per-unit-of-area rate of accumulated drainage flows (DF) in Khorezm Region in 2016-2018 ranged between 5,864 – 11,740 m³/ha amounting to 26-58% of gross water withdrawals per each irrigated hectare (14,179-16,494 m³/ha). Also remarkable is that around 92% of all accumulated drainage flows is lost to natural depressions of which only 2% is returned back to the rivers and 6% back to the canals for reuse. Specific Net irrigation water withdrawals per each irrigated hectare for the same period ranged from 4,202 to 8,316 m³/ha or 26-58% of the gross irrigation water withdrawals (EBRD and IWMI 2019).

Irrigation pump stations and hydro posts



It should be noted that the water extraction for irrigation is a very important aspect for the livelihood of the rural population in the province. The total irrigated area is 267.7 thousand ha of which 176.0 thousand ha (WB 2003) are under lift irrigation using a network of pumping stations. While most irrigated areas are still under cotton and wheat cultivation, there is a clear pattern nowadays towards crop diversification with the areas under these two crops gradually decreasing.

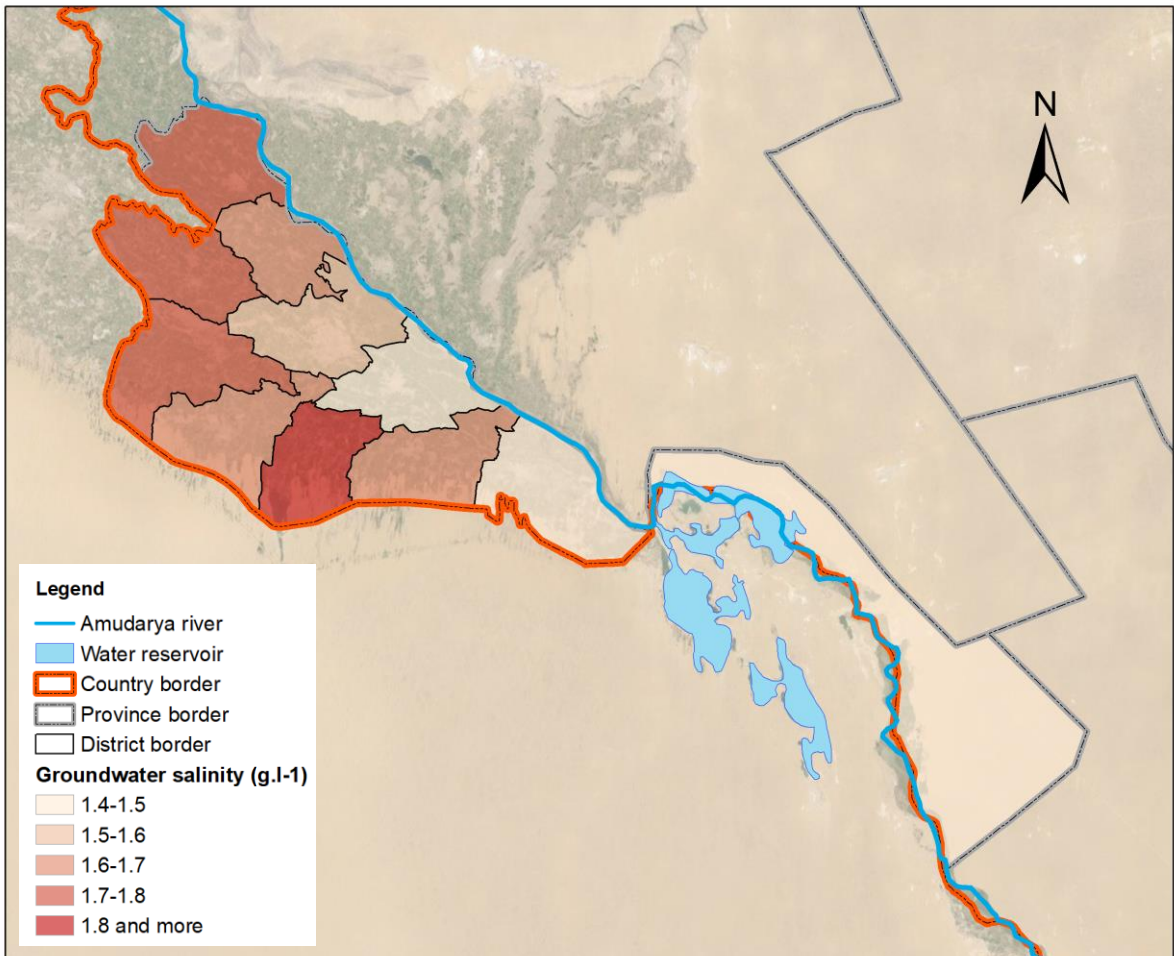
Groundwater depth (1991-2017)



Source: Hamidov et. al (2020)

A generally shallow groundwater table is, on the one hand, the consequence of excessive application of irrigation water. On the other hand, it is a result of imperfect drainage, which in Khorezm is caused by several factors. Since, due to institutional shortcomings, irrigation water is sometimes not available when needed, farmers in Khorezm tend on such occasions to manually block drains and irrigation canals and maintain high soil moisture prior to and after the planting of cotton. In recent years, increases in the land areas of the province with average groundwater level (GWL) values of 1-1.5 m and 1.5-2.0 m during the growing season have been insignificant, while areas with average GWL values of 0.0 - 1.0 m, 2.0 - 3.0 m and 3.0 - 5.0 m have somewhat decreased. Furthermore, the general drainage system is also dysfunctioning and consequently about 34 % of the area of Khorezm has a saline and shallow (<1.0 m) groundwater table (Forkutsa et al. 2009).

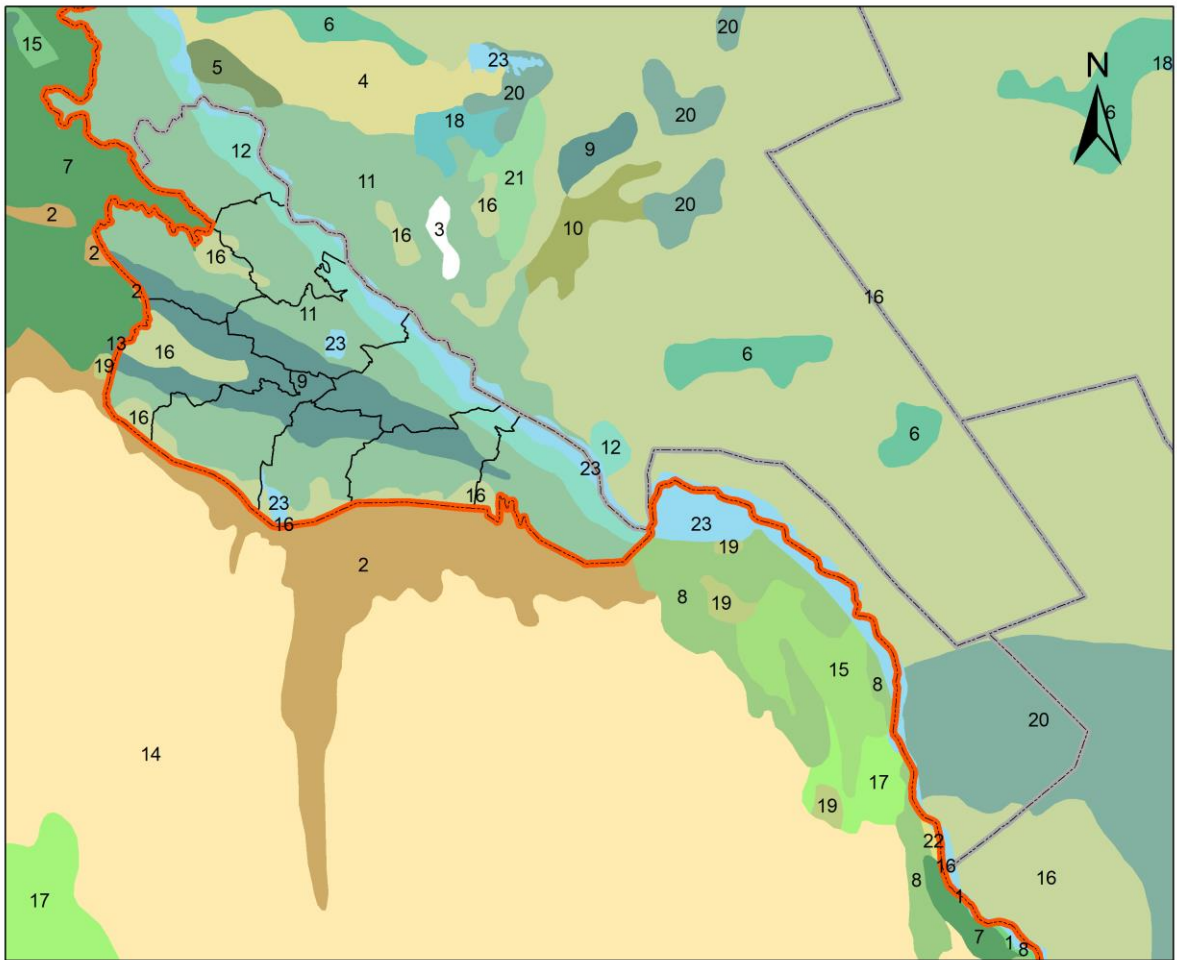
Groundwater salinity (1991-2017)



Source: Hamidov et al. 2020.




Groundwater salinity in the province during the growing season has been on the rise. In the period of 2018 to 2021, areas with the groundwater mineralization (GWM) of 0-1 g/l decreased from 30.9 to 13.7%, while those with GWM of 1-3 g/l and 3-5 g/l increased from 66.4 to 83.2%, and 2.6 to 2.9-5.7%, respectively. There were almost no areas with GWM of more than 5 g/l.

Main soil types


























Source: ICARDA (2007)

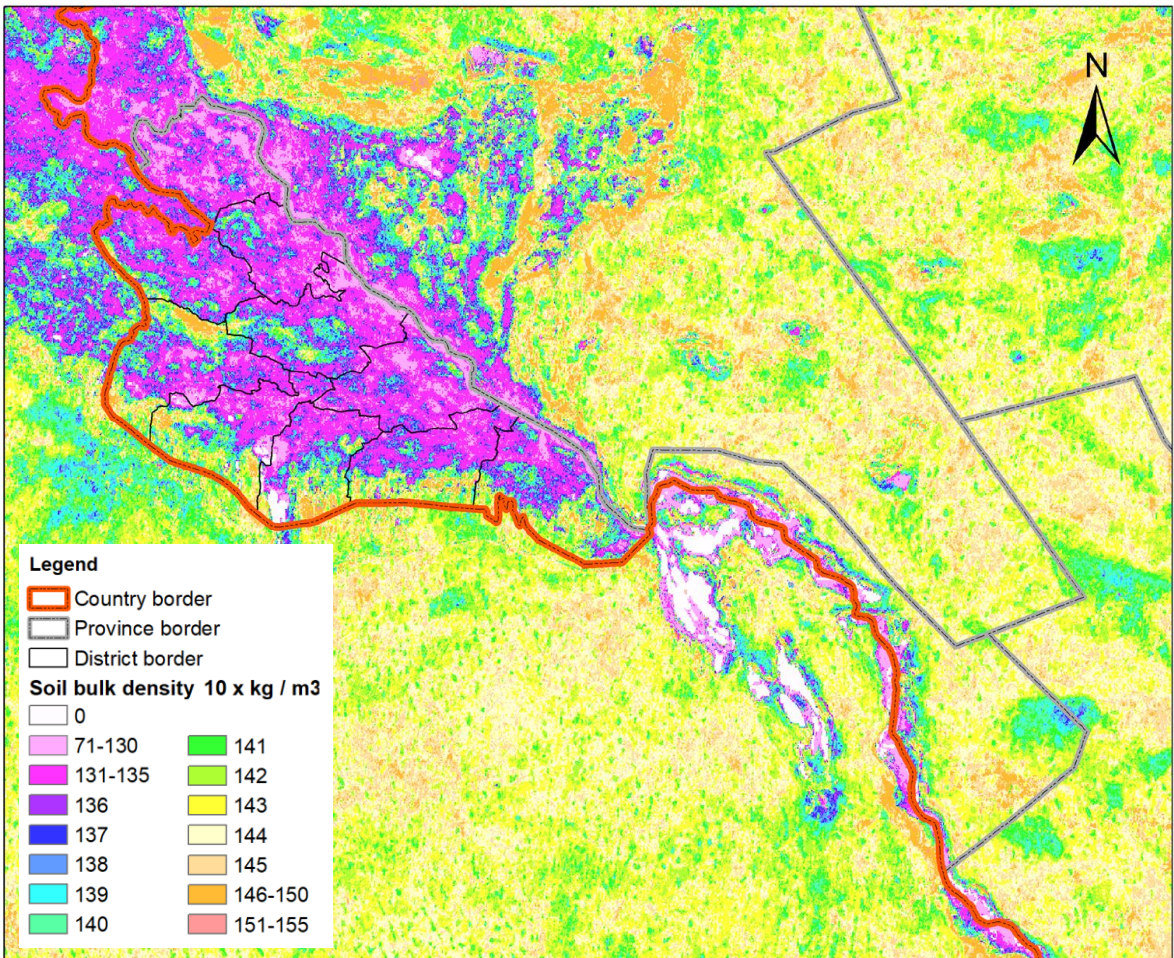
Legend

-  Country border
-  Province border
-  District border

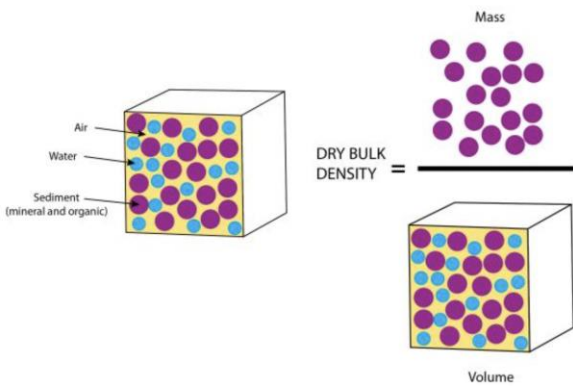
Soil type

-  1, Alluvial desert soil
-  2, Blown and poor fixed sand
-  4, Grey-brown eroded skeletal
-  5, Grey-brown solonchak
-  6, Grey brown desert weak stony soils
-  7, Irrigated meadow
-  8, Light-brown desert subtropic
-  9, Meadow-oasis saline and leached
-  10, Meadow-takir on alluvium and proluvium
-  11, Meadow soils
-  12, Meadow soils of the flood plains
-  13, Moist-meadow (swamp-meadow) desert
-  14, Sand (50%) and sandy desert (50%)
-  15, Sand (60%) solonchak (40%)
-  15, Sand (60%) and light-brown (40%)
-  16, Sands
-  17, Sandy desert (60%) and light-brown (40%)
-  18, Shor and other solonchaks
-  19, Solonchak
-  20, Takir-like and takirs
-  21, Takir-meadow saline on alluvium
-  22, Usual light-brown irrigated
-  23, Water

Soil bulk density



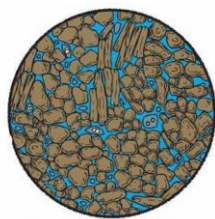
Source: OpenLandMap.org (Hengl 2018a).



The soil bulk density, also known as dry bulk density, is the weight of dry soil divided by total soil volume. The total soil volume is the combined volume of solids and pores which may contain air or water, or both. The average values of air, water and solid in soil are readily measured and are a useful indication of a soils physical condition.



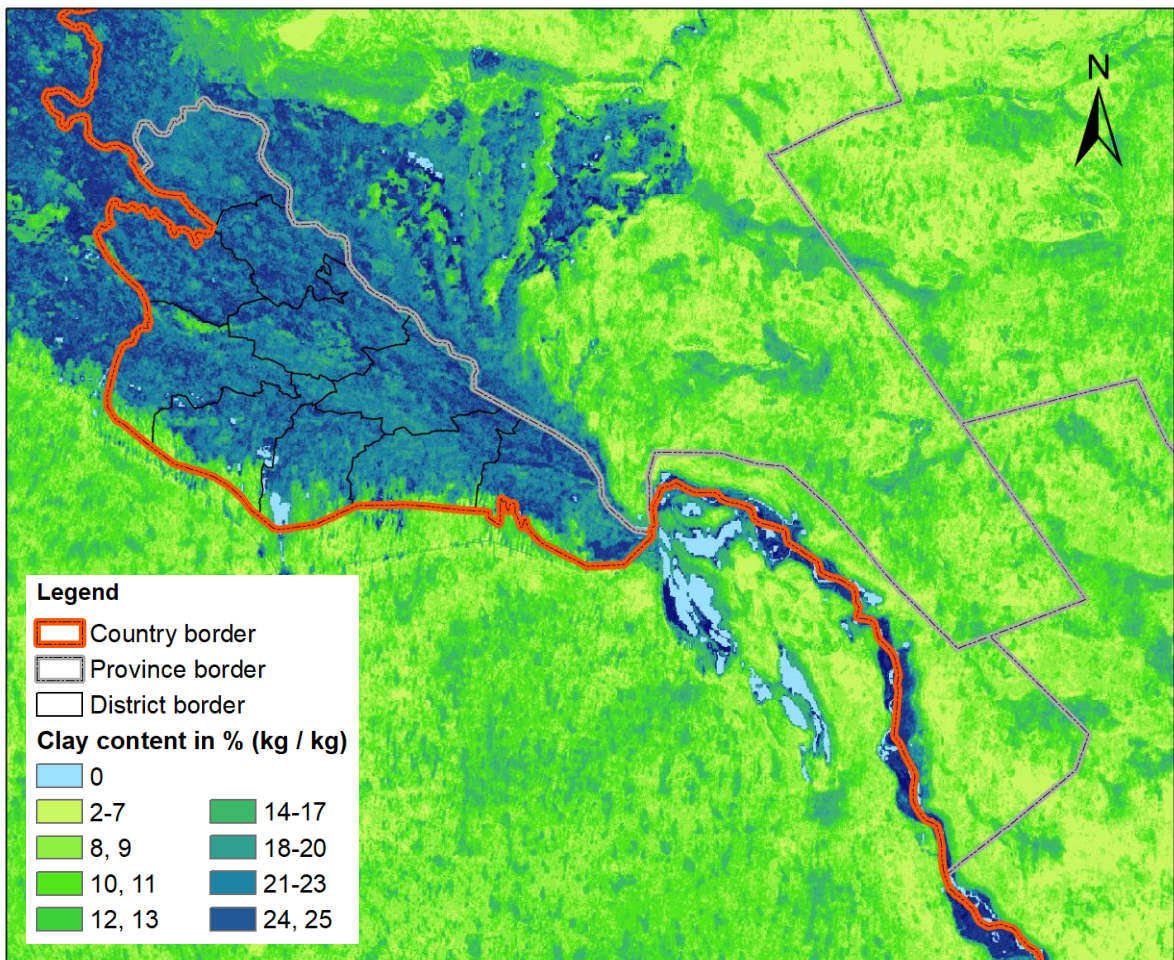
Lower bulk density
Lower weight
More pore space



Higher bulk density
Higher weight
Less pore space

OpenLandMap.org is a data portal to the world's environmental data representing land mask (land cover, vegetation, soil, climate, terrain data and similar). OpenLandMap.org is the web- mapping component of the OpenGeoHub GIS for land data (Hengl 2018a).

Clay content in soil



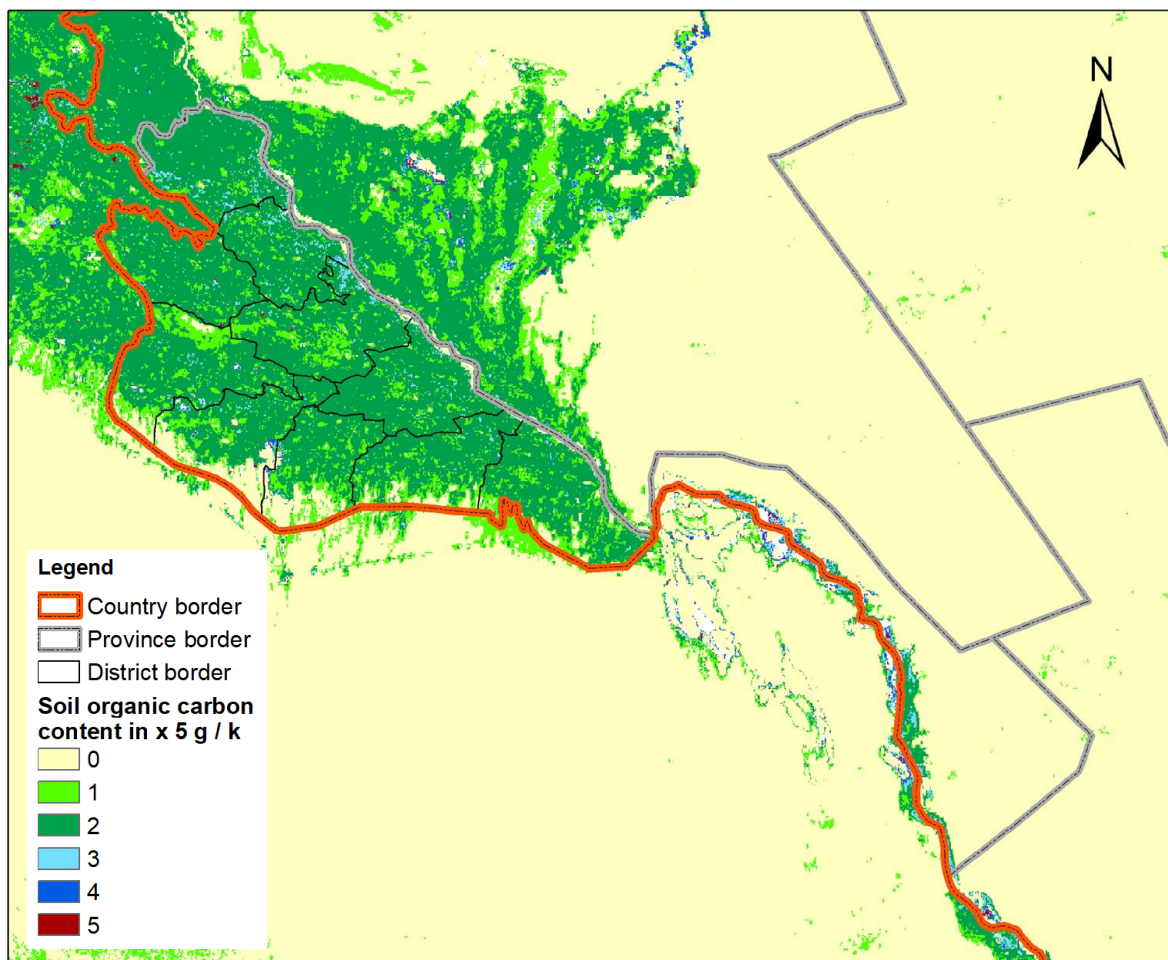
Source: *OpenLandMap.org* (Hengl 2018b).



Clay is a fundamental driver of many soil properties and in many ways defines what a soil is capable of growing and storing. The clay fraction in soils are any mineral particles less than 2 microns in size. As a result, the combined clay fraction has a significant surface area and therefore a large capacity for nutrient and carbon storage. The clay fraction also provides physical protection for soil microbes against predation.

OpenLandMap.org is a data portal to the world's environmental data representing land mask (land cover, vegetation, soil, climate, terrain data and similar). OpenLandMap.org is the web-mapping component of the OpenGeoHub GIS for land data (Hengl 2018a).

Soil organic carbon content



Source: *OpenLandMap.org* (Hengl and Wheeler 2018).

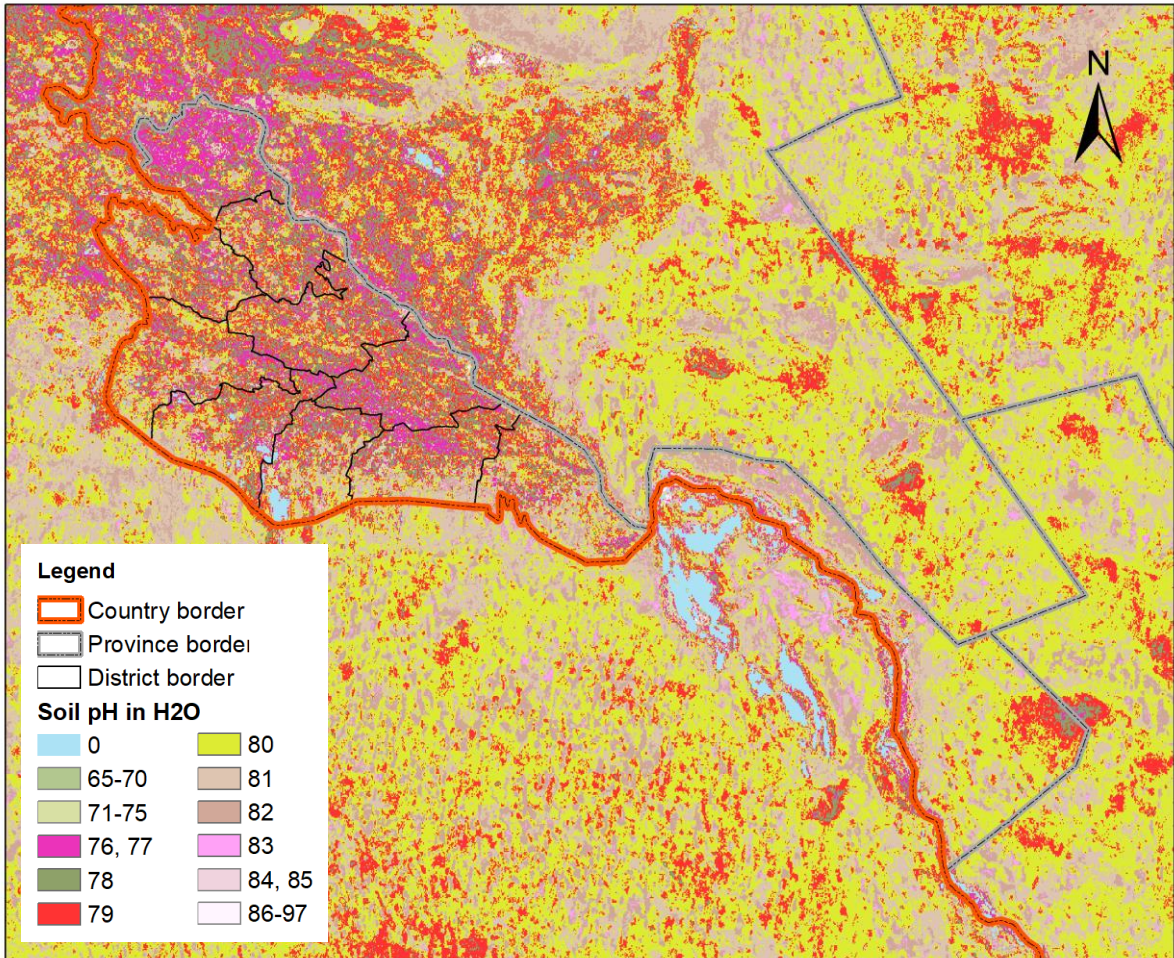


Soil organic carbon is a measurable component of soil organic matter. Organic matter makes up just 2–10% of most soil's mass and has an important role in the physical, chemical and biological function of agricultural soils.

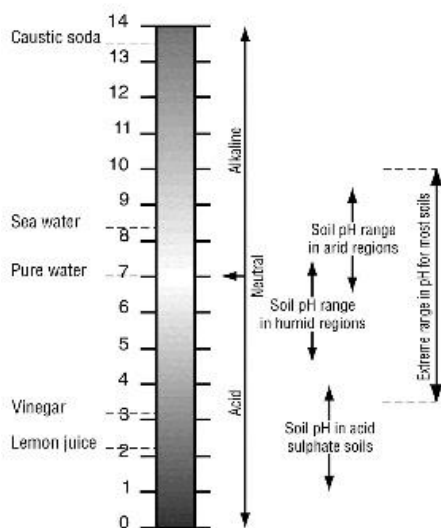
Organic matter contributes to nutrient retention and turnover, soil structure, moisture retention and availability, degradation of pollutants, and carbon sequestration.

OpenLandMap.org is a data portal to the world's environmental data representing land mask (land cover, vegetation, soil, climate, terrain data and similar). OpenLandMap.org is the web-mapping component of the OpenGeoHub GIS for land data (Hengl 2018a).

Soil pH in H₂O



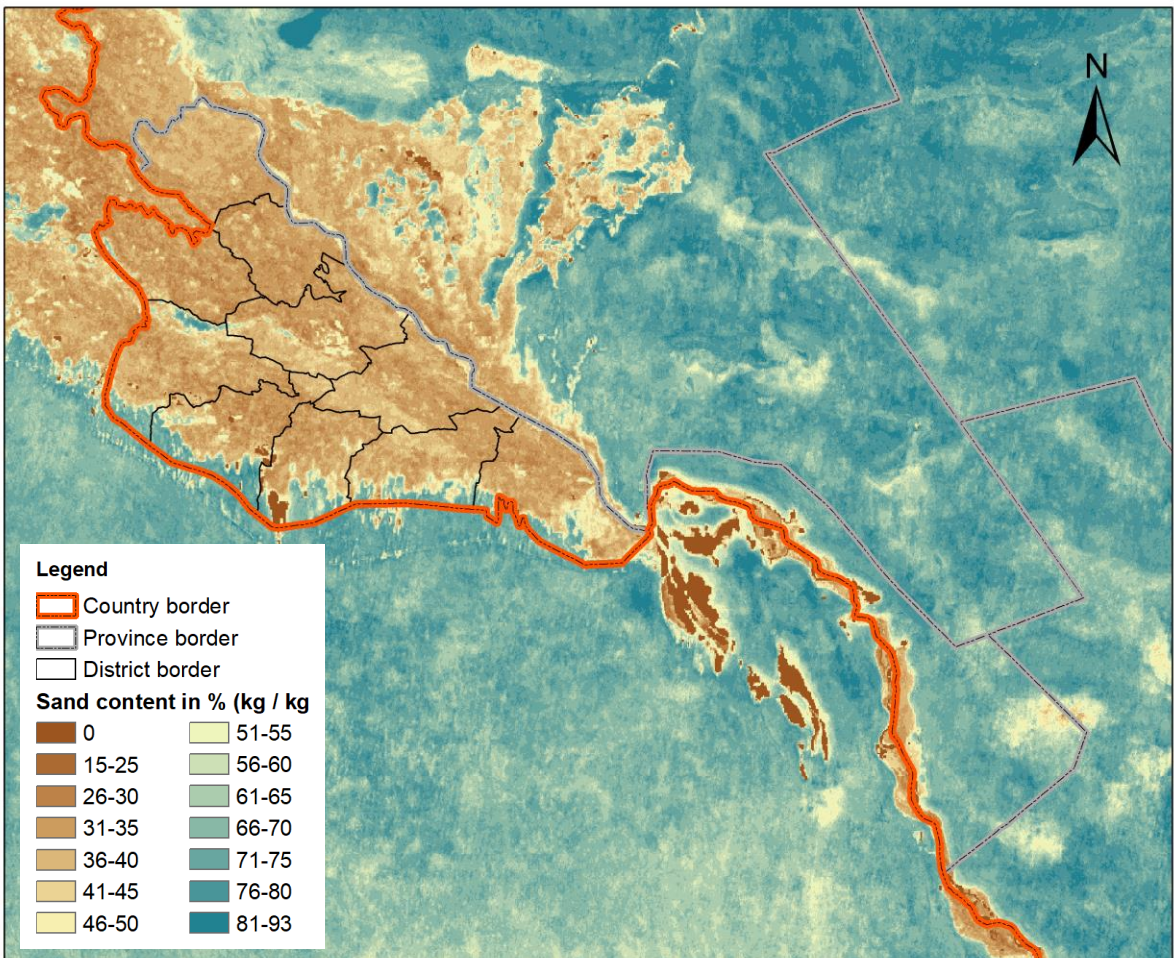
Source: OpenLandMap.org (Hengl 2018c).



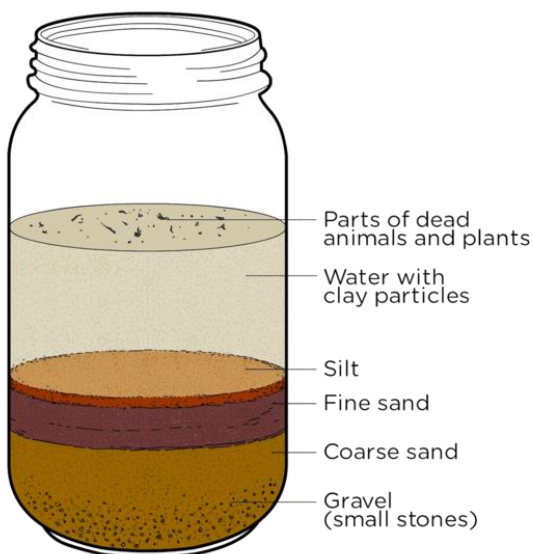
Soils can be naturally acid or alkaline, and this can be measured by testing their pH value. Having the correct pH is important for healthy plant growth. Being aware of the long-term effects of different soil management practices on soil pH is also important. Research has demonstrated that some agricultural practices significantly alter soil pH.

OpenLandMap.org is a data portal to the world's environmental data representing land mask (land cover, vegetation, soil, climate, terrain data and similar). OpenLandMap.org is the web-mapping component of the OpenGeoHub GIS for land data (Hengl 2018a).

Soil sand content



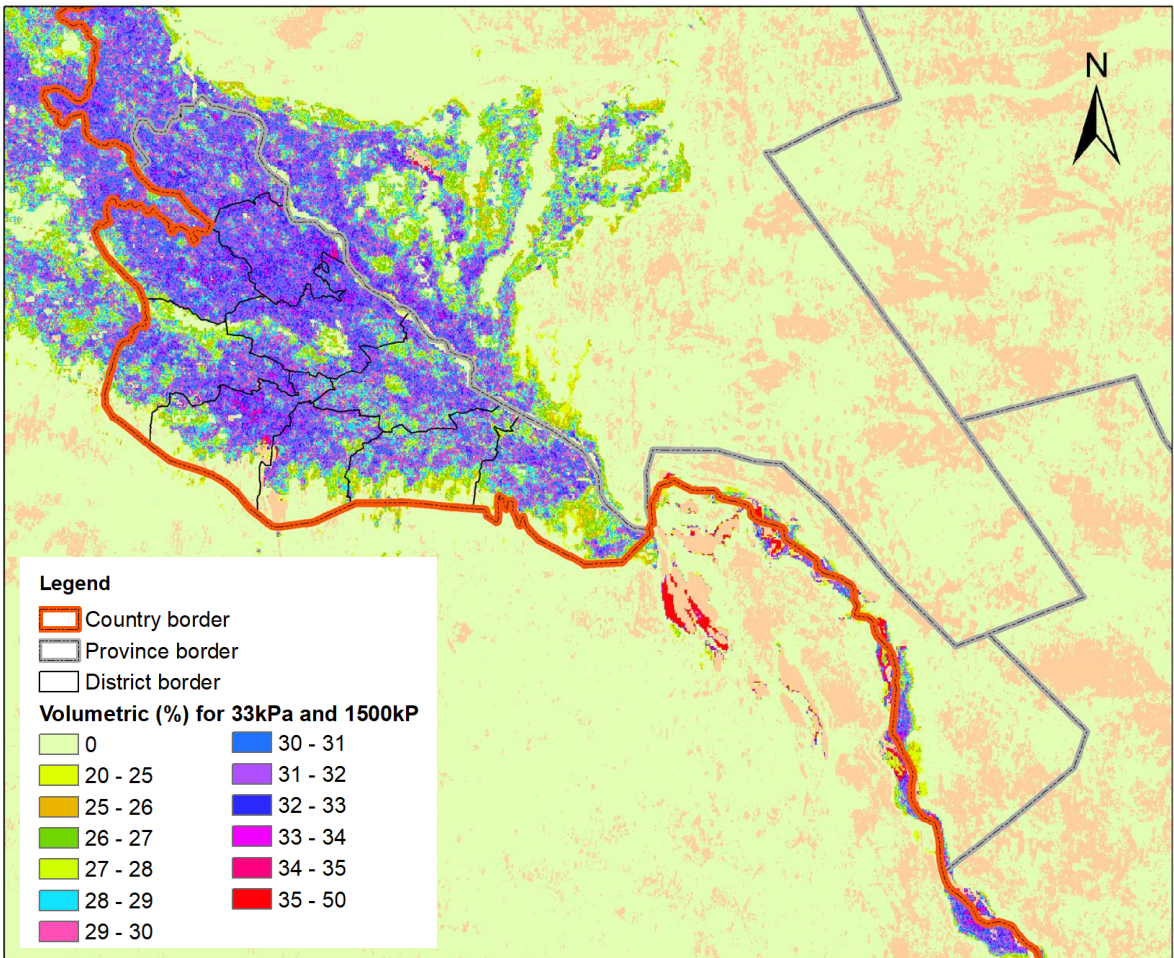
Source: *OpenLandMap.org* (Hengl 2018d).



Sand is a naturally occurring granular material composed of finely divided rock and mineral particles. A soil containing more than 85% sand-sized particles by mass is called sandy.

OpenLandMap.org is a data portal to the world's environmental data representing land mask (land cover, vegetation, soil, climate, terrain data and similar). *OpenLandMap.org* is the web-mapping component of the *OpenGeoHub GIS* for land data (Hengl 2018a).

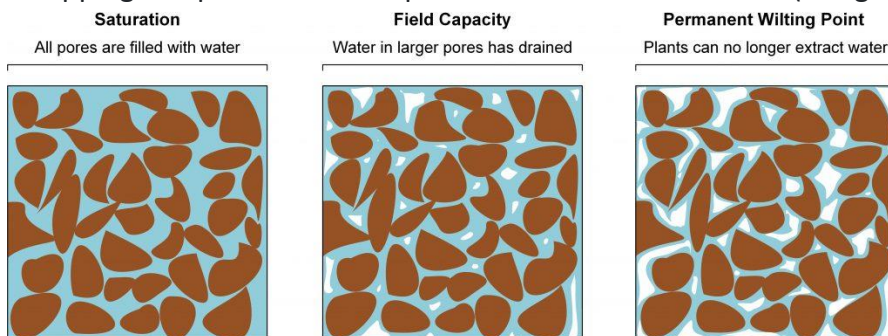
Soil water content at 33kPa



Source: *OpenLandMap.org* (Hengl and Gupta 2019).

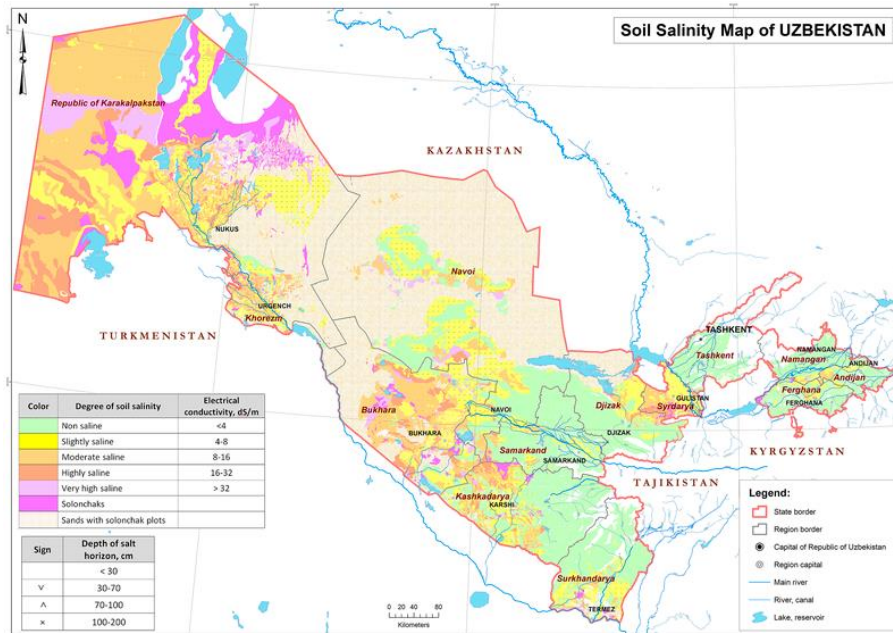
The soil water content (SWC) or soil moisture is the amount of water present in the soil. It influences plant growth, soil temperature, transport of chemicals and groundwater recharge. The two most widely used parameters for quantifying SWC or water availability for plants are i) volumetric water content; and ii) soil matric potential. Soil water content (volumetric %) for 33kPa and 1500kPa suctions predicted at 0 cm depth at 250 m resolution.

OpenLandMap.org is a data portal to the world's environmental data representing land mask (land cover, vegetation, soil, climate, terrain data and similar). OpenLandMap.org is the web-mapping component of the OpenGeoHub GIS for land data (Hengl 2018a).



Soil water content at saturation, field capacity and permanent wilting point thresholds.

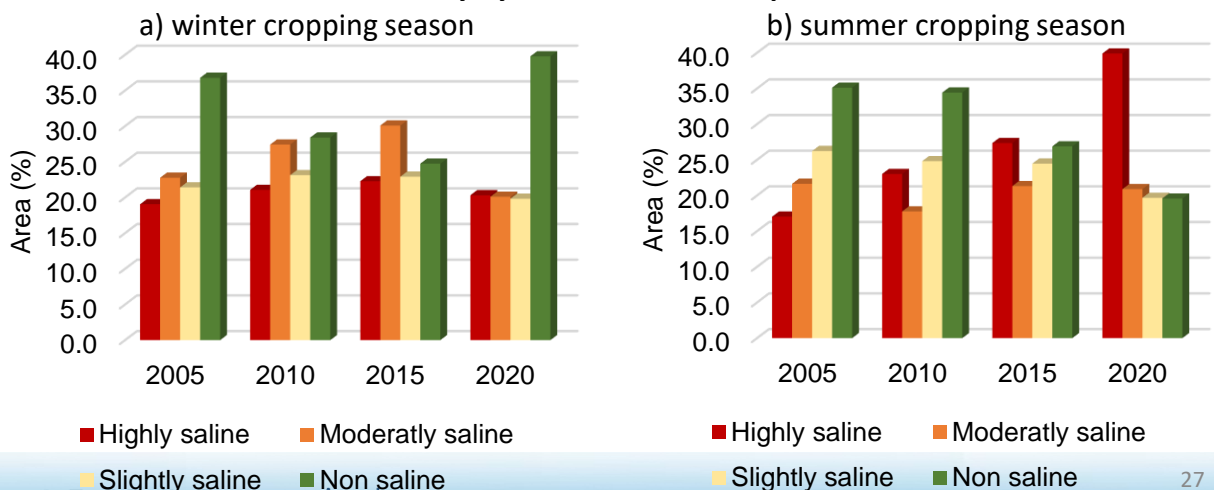
Soil salinity map of Uzbekistan



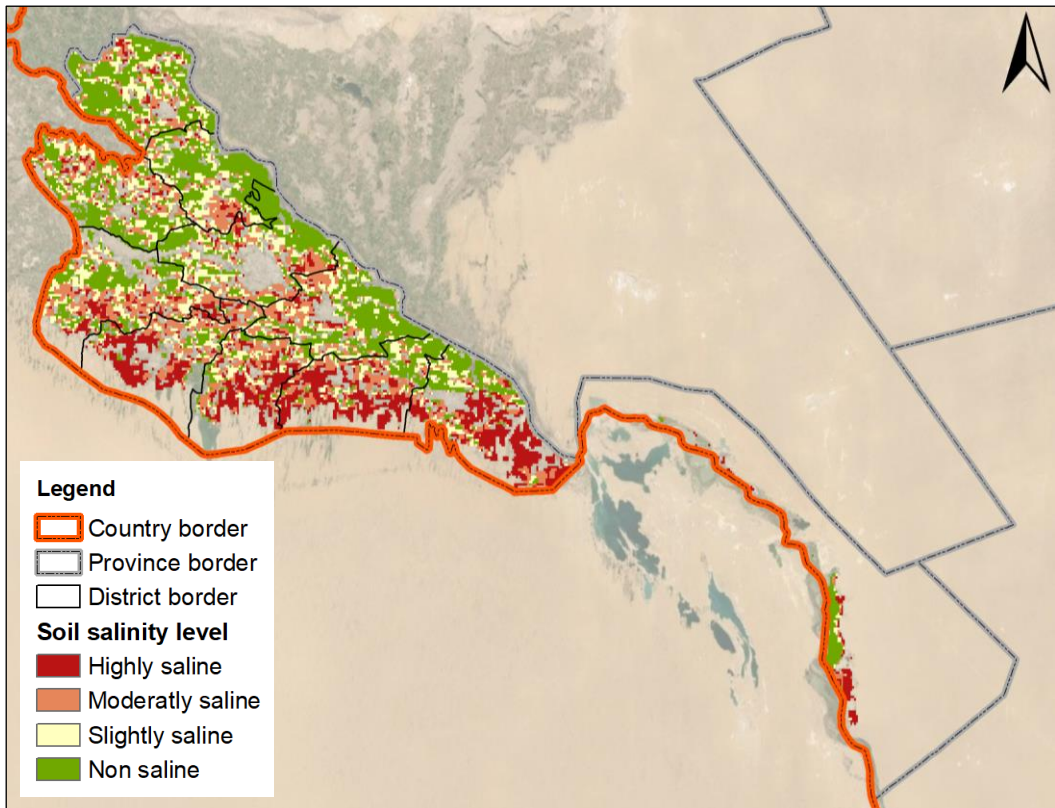
Soil salinization is one of the main environmental issues, affecting large areas in Uzbekistan. At least 46.6% of the country's irrigated land areas is affected by salinization in one way or another, with 2,5% strongly saline, 13,3% moderately saline and 30,9% slightly saline (Eltazarov 2016). One of the areas most affected by soil salinization is Khorezm province. For one, its entire irrigated area (100 %) is prone to secondary salinization, for another, 81 % of the area is also waterlogged. Among the causes of it are underperforming drainage and irrigation systems, non-compliance with agronomic practices, on-farm water overuse, etc. The underlying processes associated with secondary soil salinization and waterlogging are caused by shallow groundwater tables (between 0.5 m and 2.0 m). The amelioration of soils is complicated by a low thickness of the fine-earth layer, the salinity of the underlying soils and a high gypsum content.

The charts below and on a series of pages that follow next provide a comparative multi-year picture of soil salinity changes using the Vegetation Soil Salinity Index (VSSI) based on MODIS satellite imagery. For VSSI calculations and soil salinity mapping, the two 3-month reference periods of March-May and June-August are used to denote the winter and summer cropping seasons, respectively. The visualizations that follow next are also provided for Khorezm based on median VSSI values.

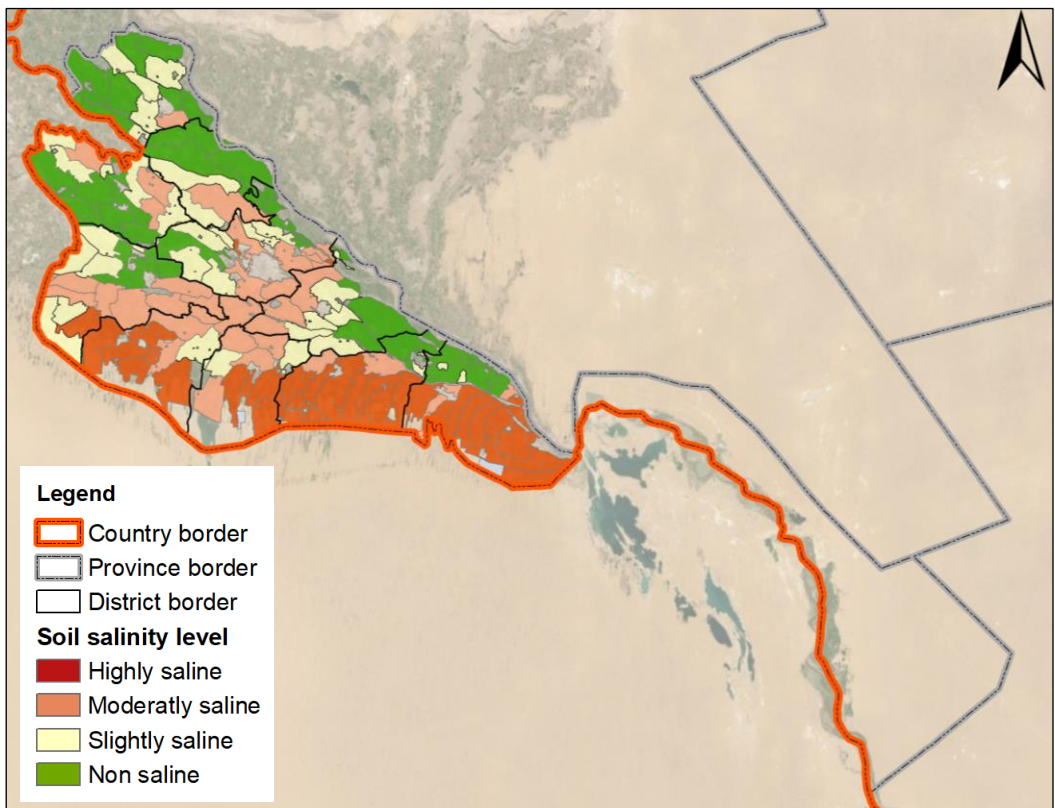
Soil salinity dynamics in Khorezm province



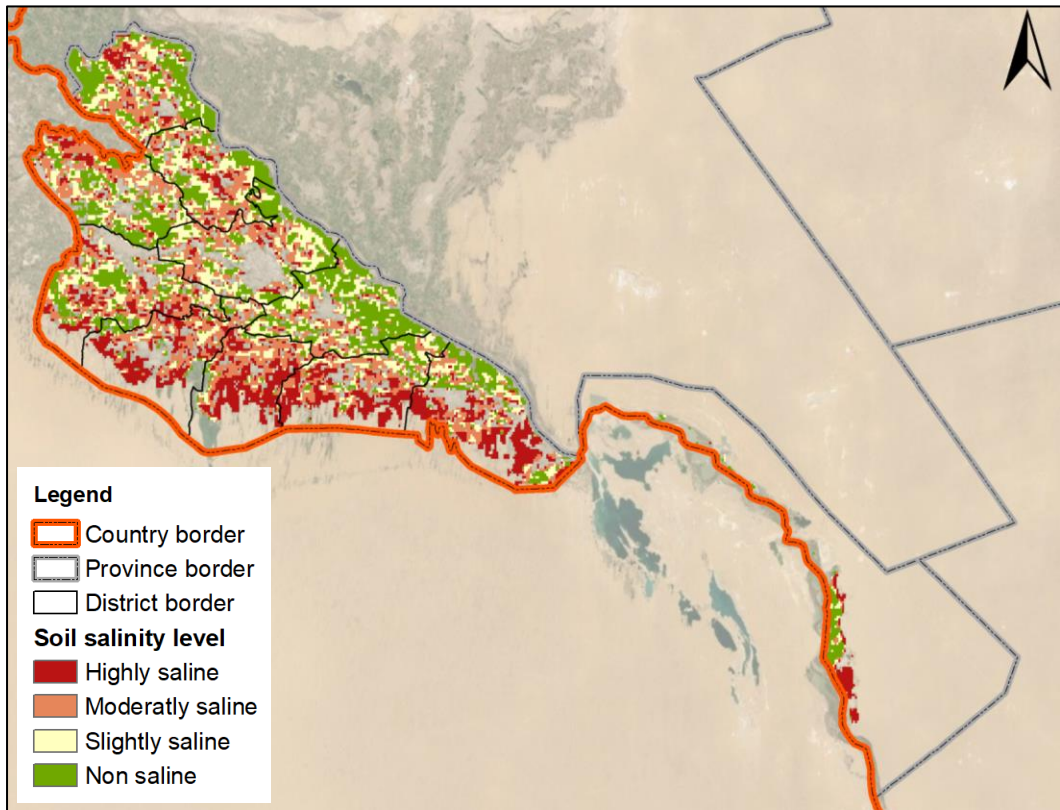
Soil salinity in 2005 (winter cropping season)



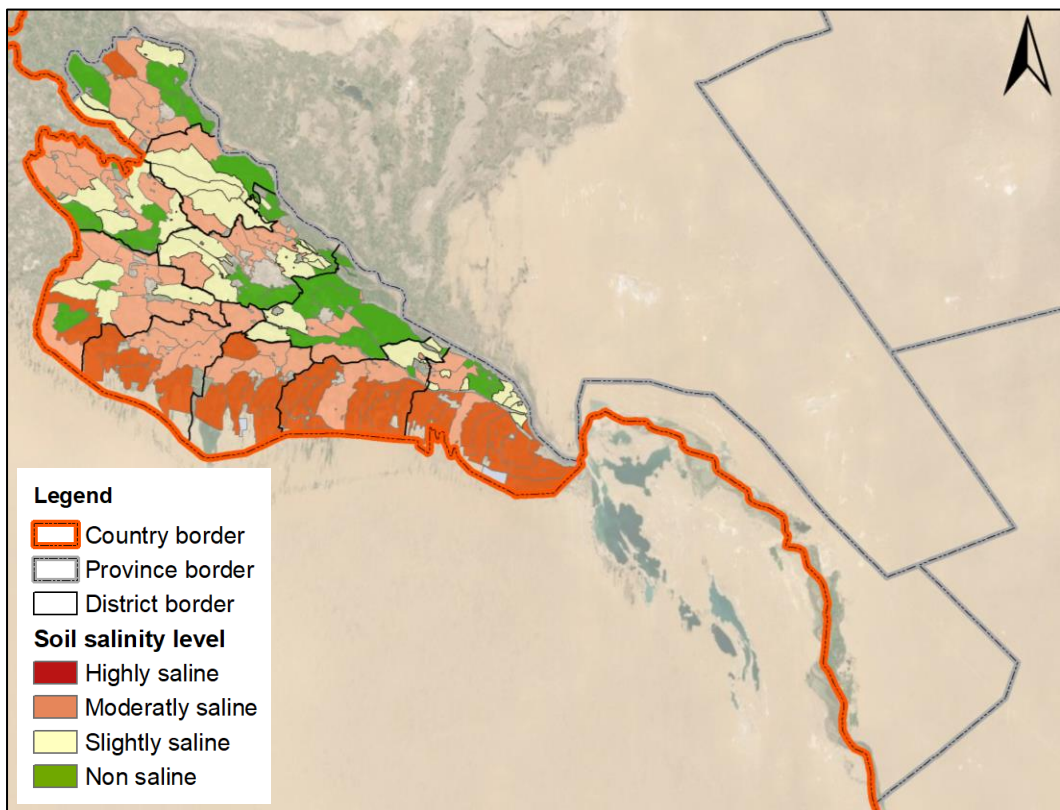
Soil salinity in 2005 by district boundary (winter cropping season)



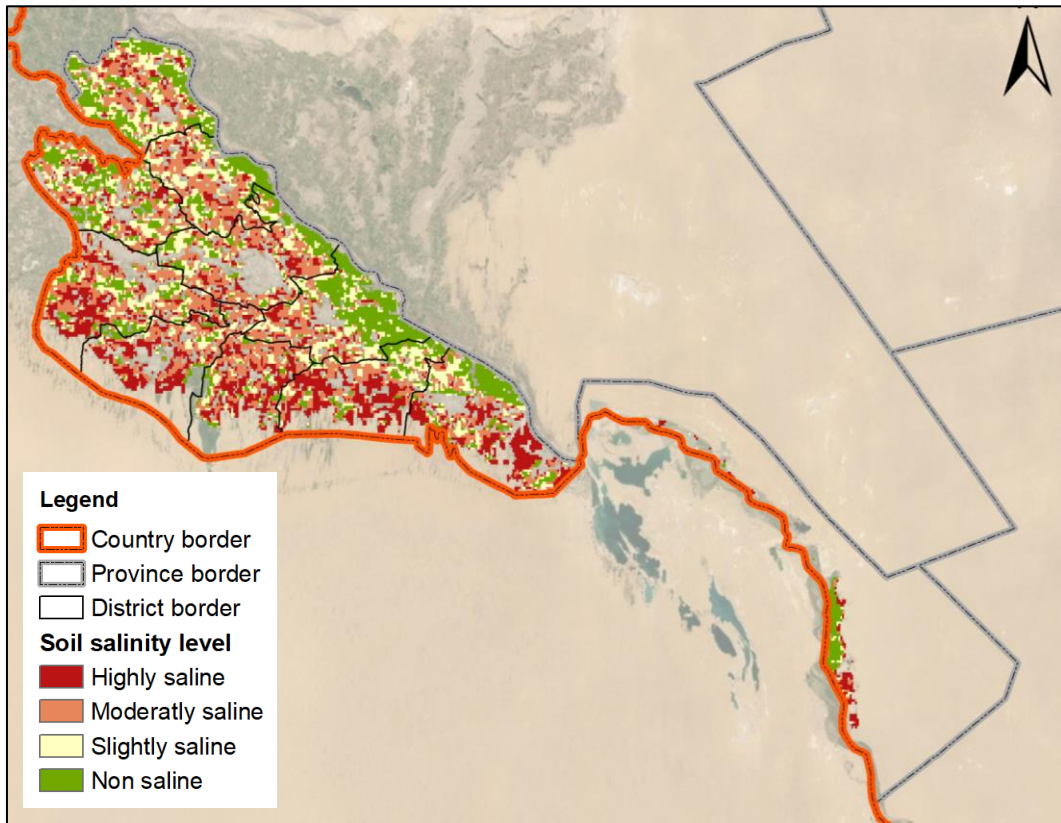
Soil salinity in 2010 (winter cropping season)



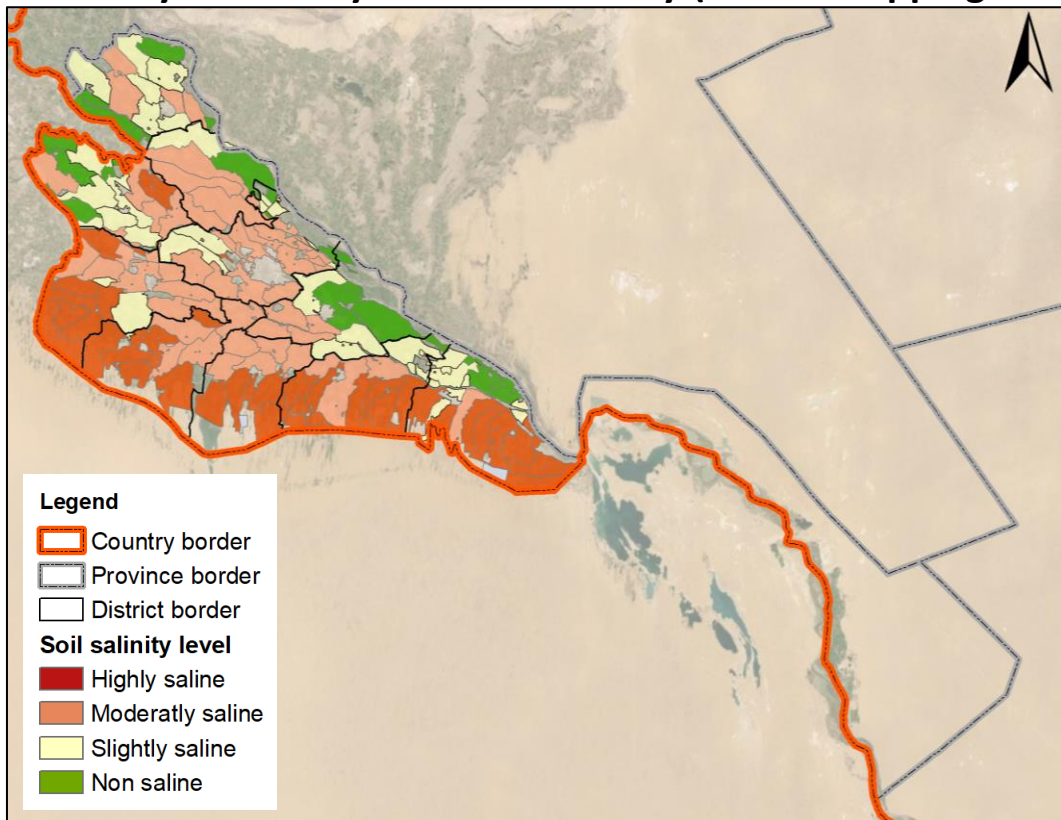
Soil salinity in 2010 by district boundary (winter cropping season)



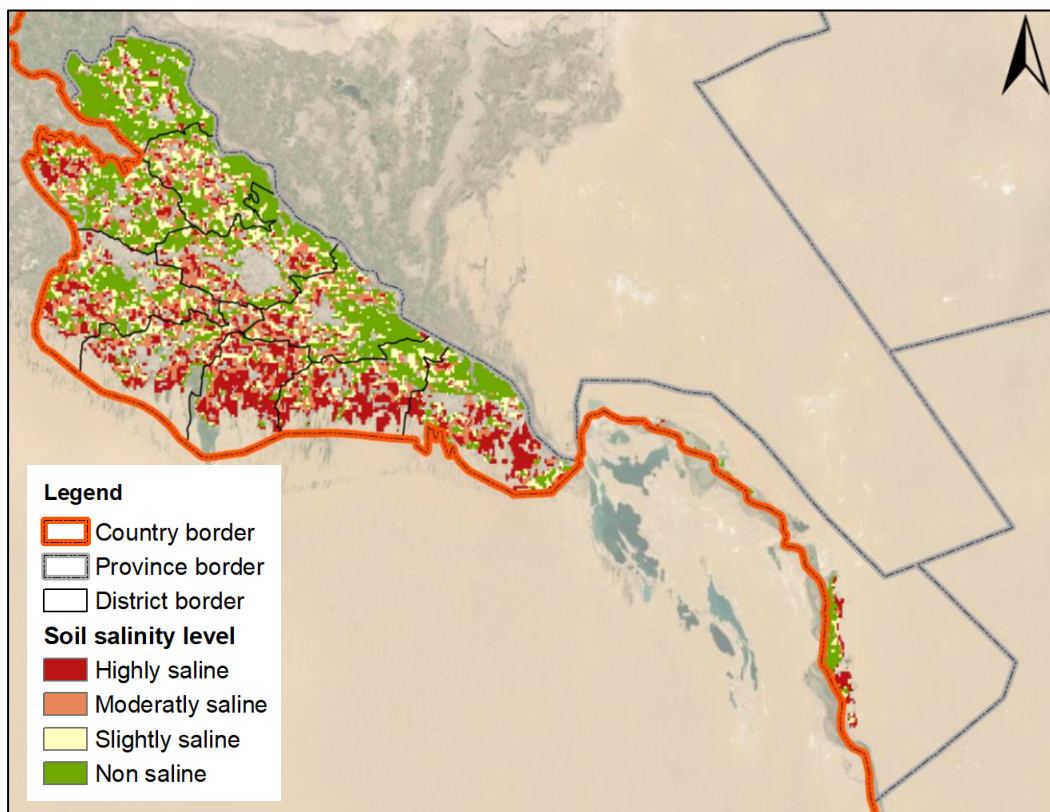
Soil salinity in 2015 (winter cropping season)



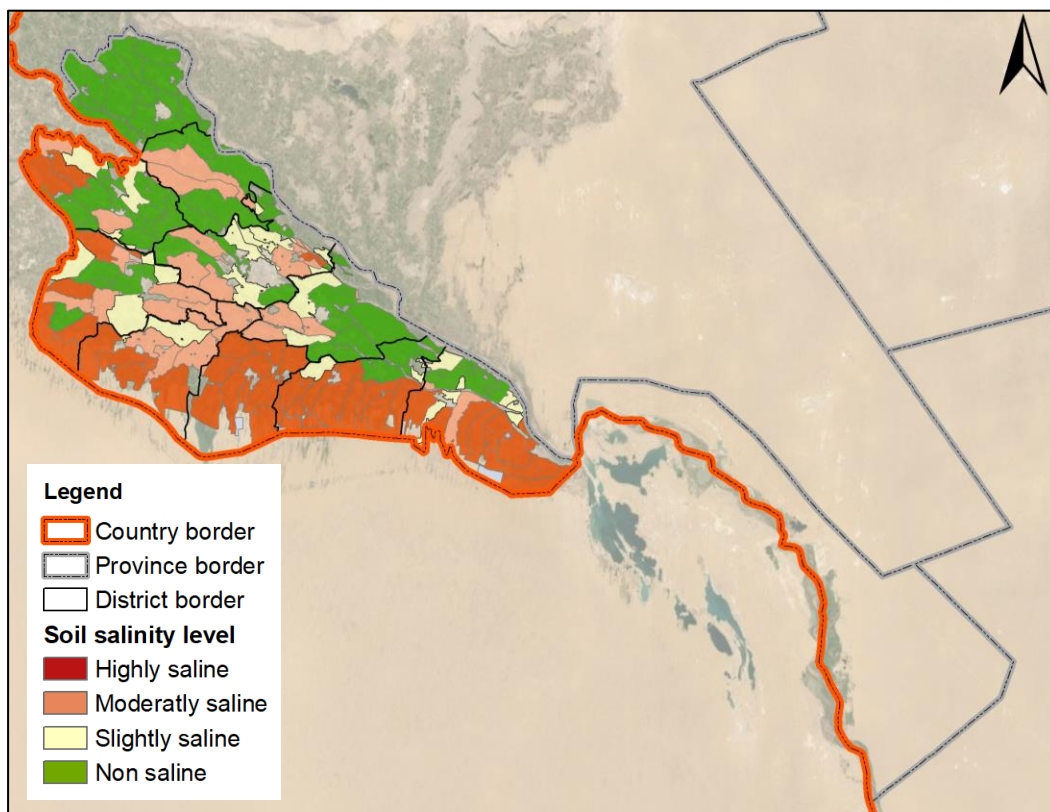
Soil salinity in 2015 by district boundary (winter cropping season)



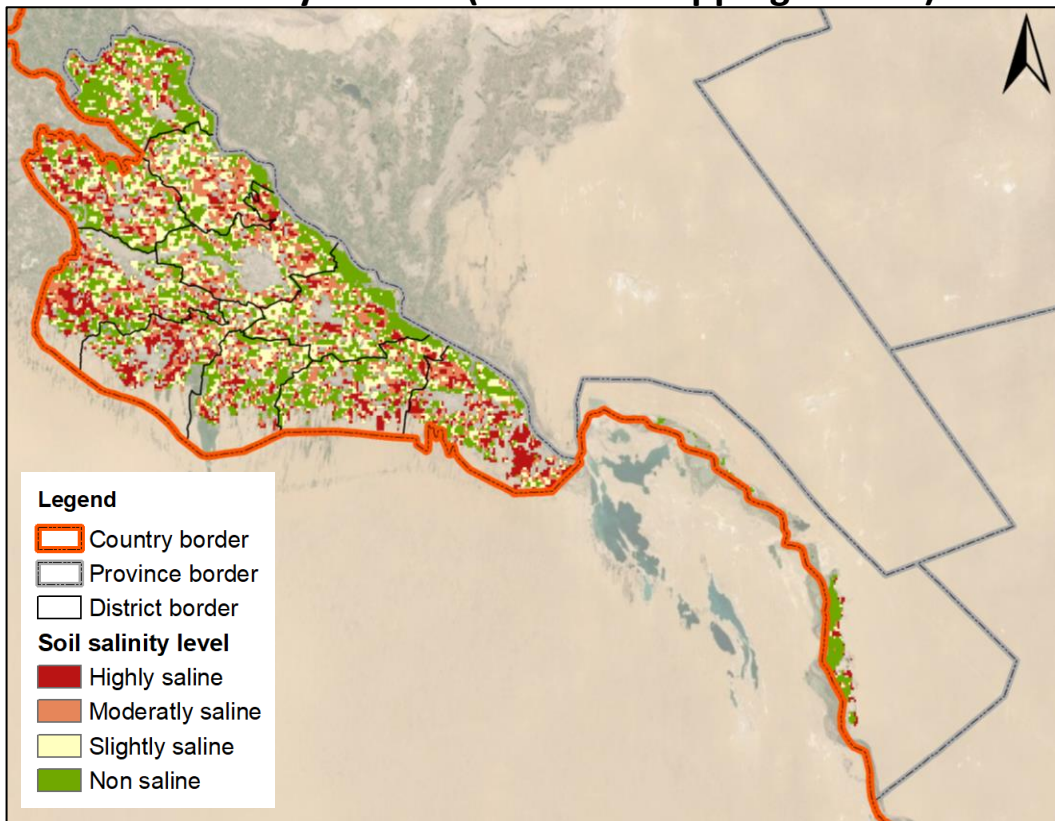
Soil salinity in 2020 (winter cropping season)



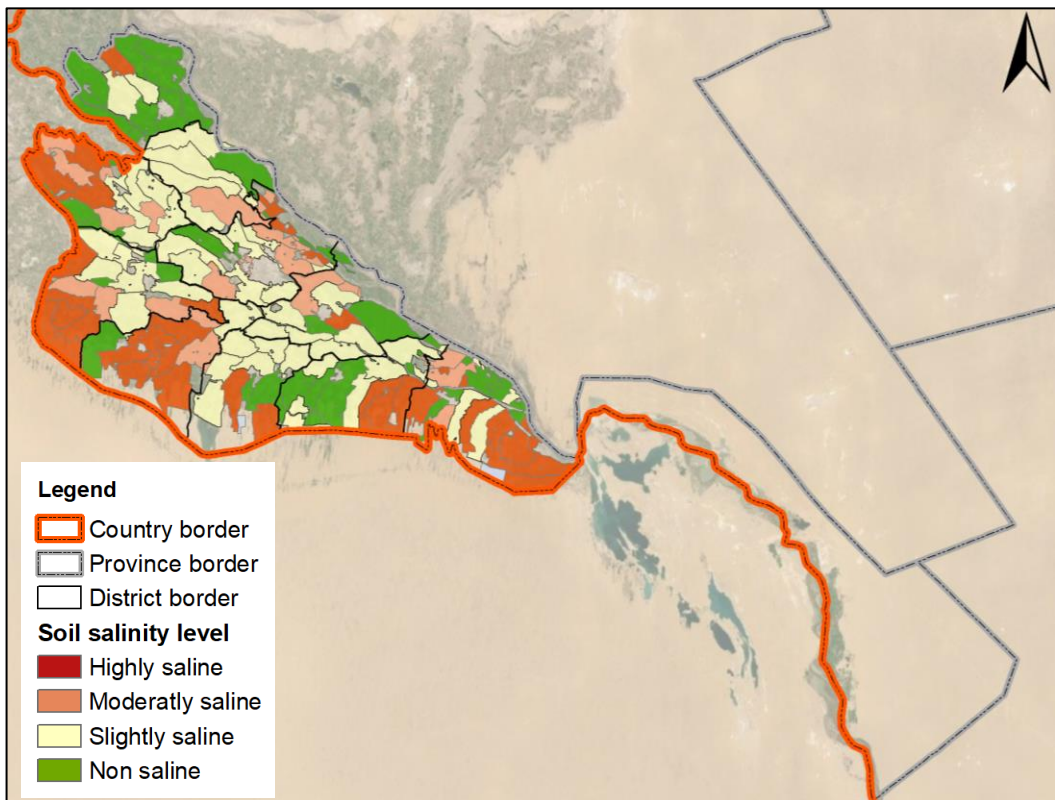
Soil salinity in 2020 by district boundary (winter cropping season)



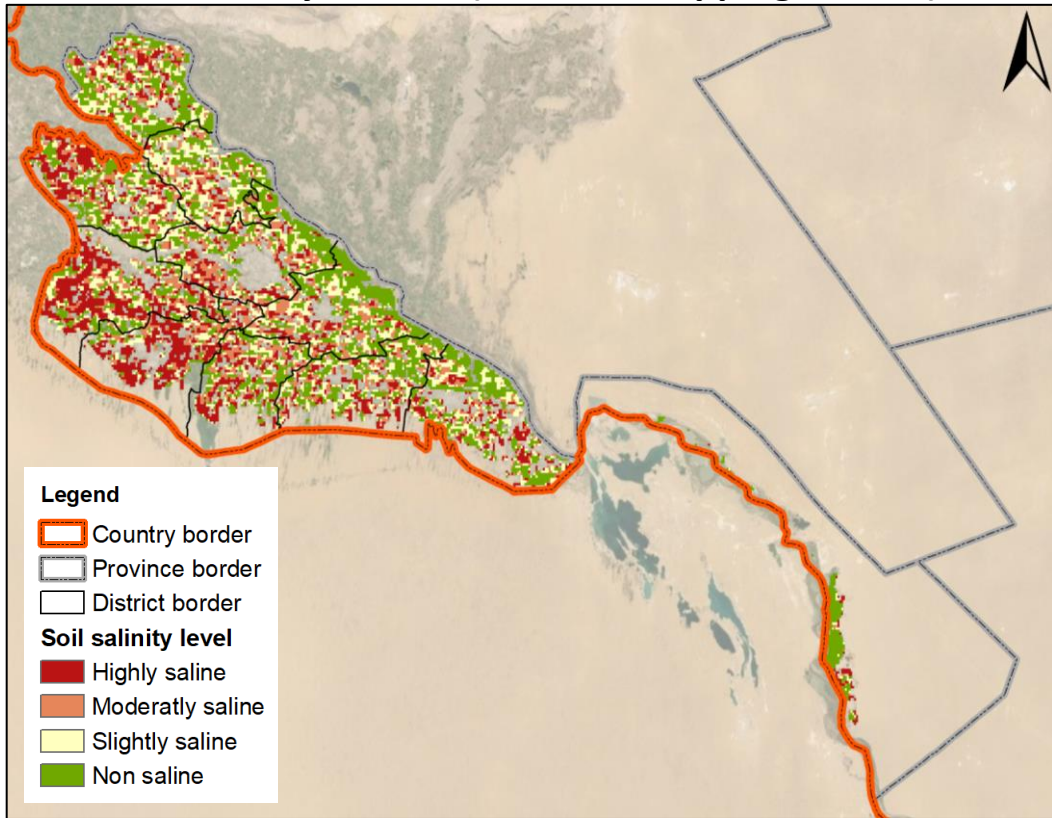
Soil salinity in 2005 (summer cropping season)



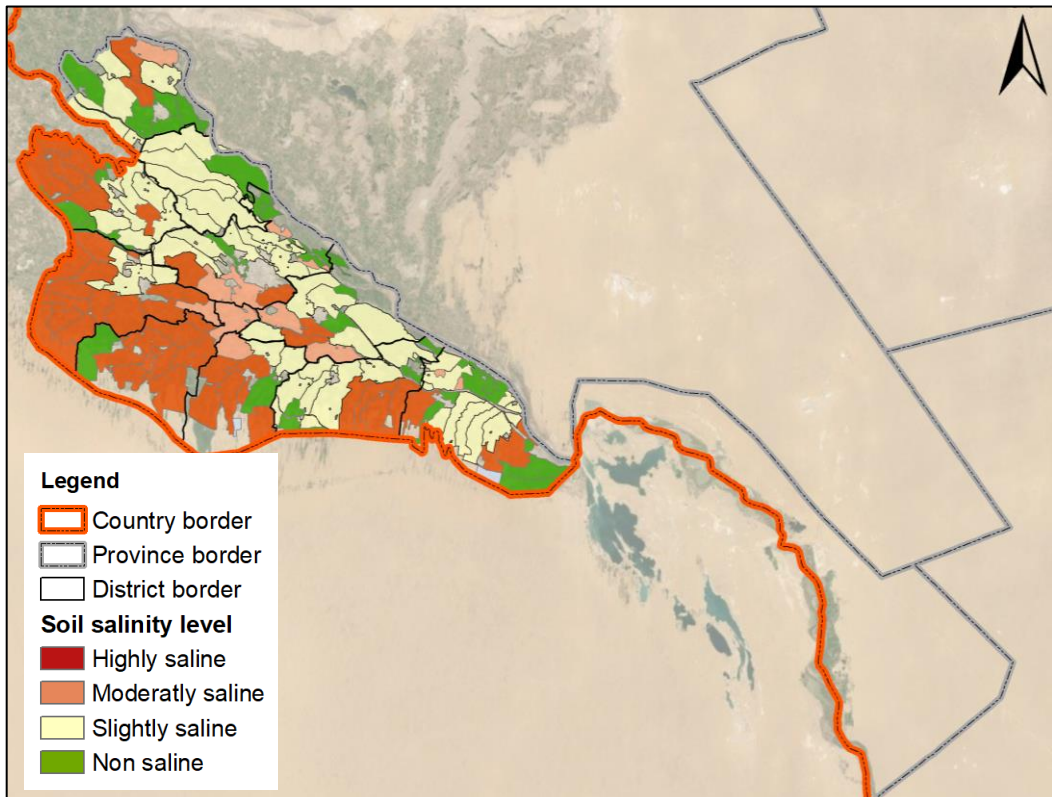
Soil salinity in 2005 by district boundary (summer cropping season)



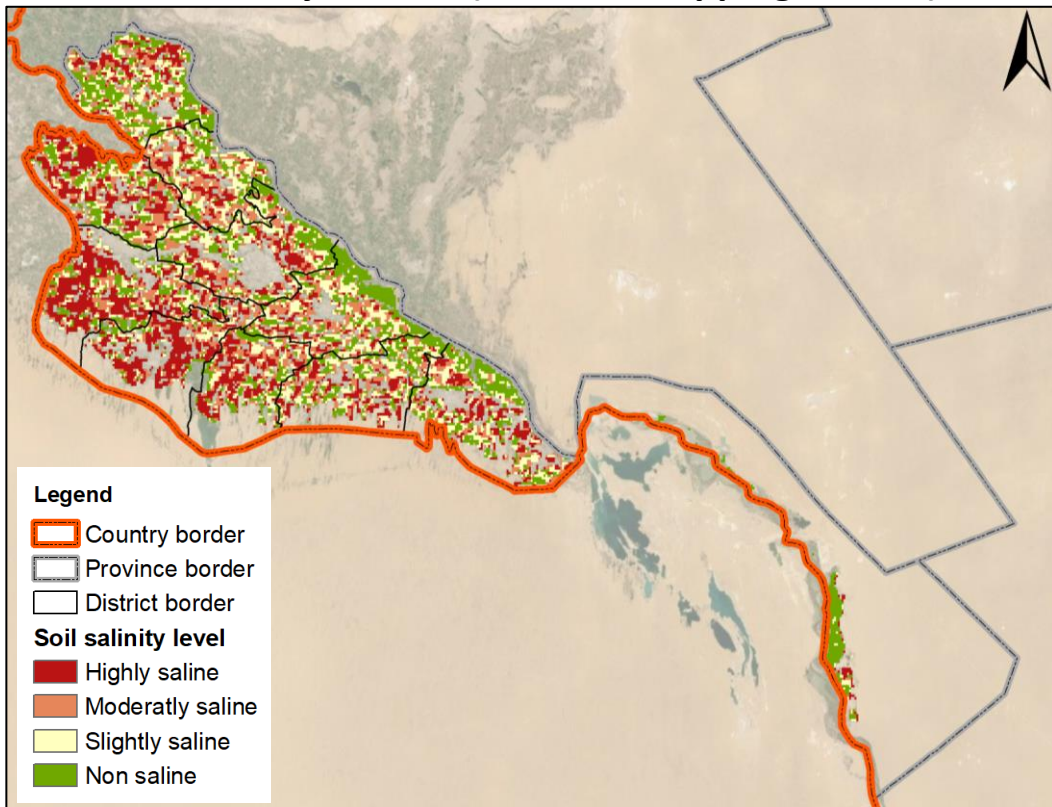
Soil salinity in 2010 (summer cropping season)



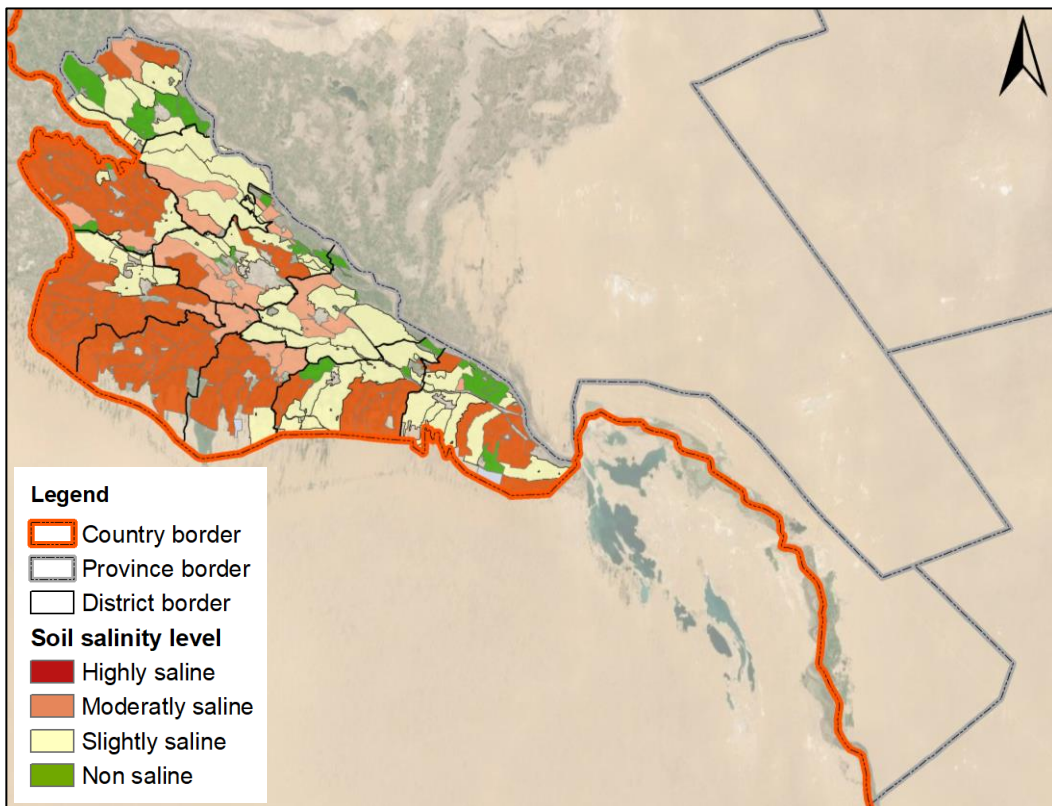
Soil salinity in 2010 by district boundary (summer cropping season)



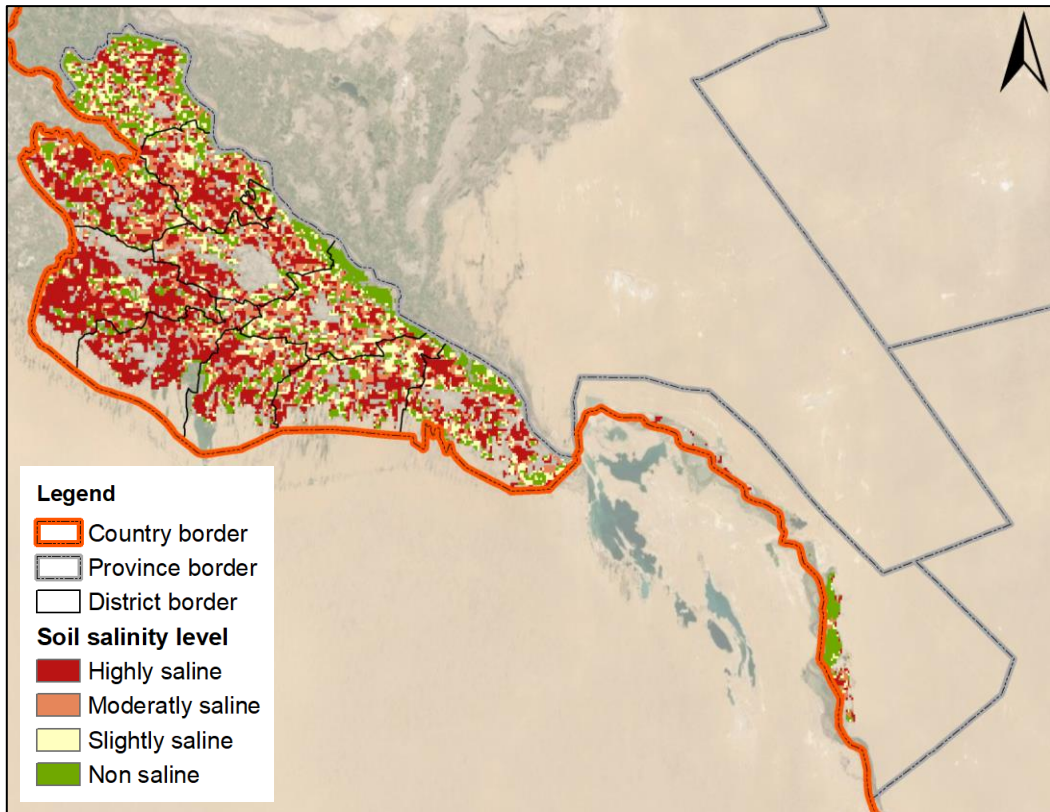
Soil salinity in 2015 (summer cropping season)



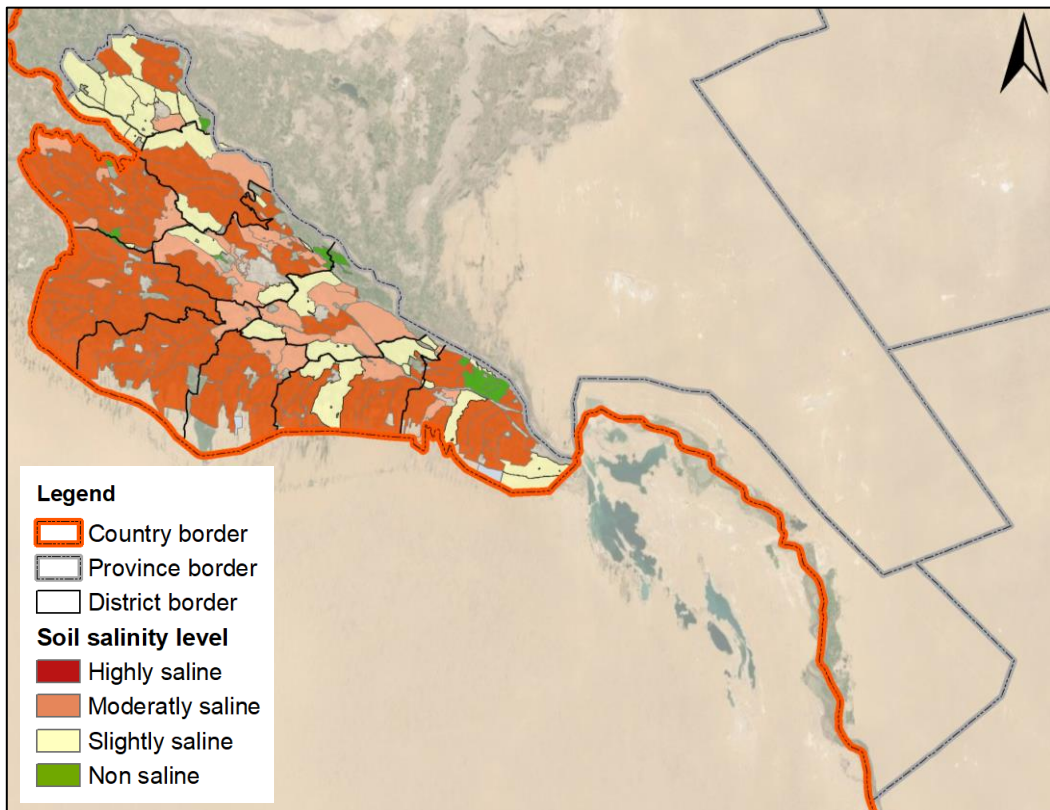
Soil salinity in 2015 by district boundary (summer cropping season)



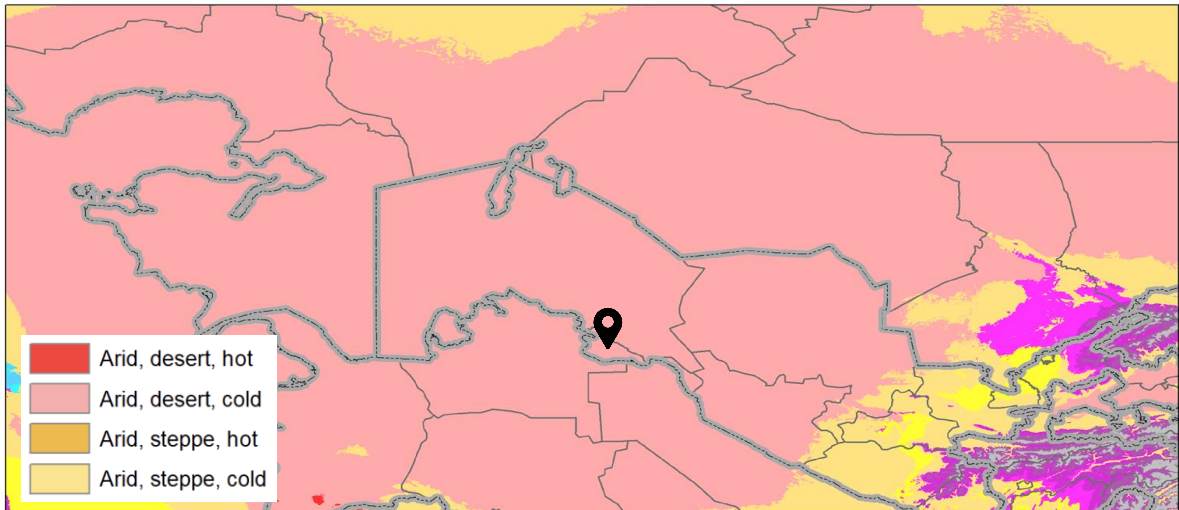
Soil salinity in 2020 (summer cropping season)



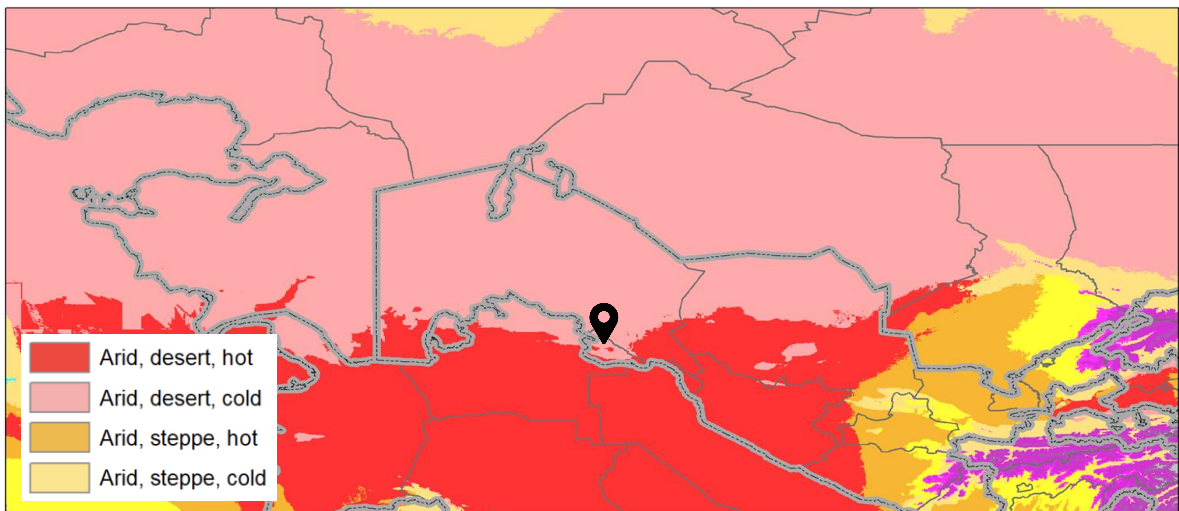
Soil salinity in 2020 by district boundary (summer cropping season)



Climate classification, present (1980-2016)



Climate classification, future (2070-2100)



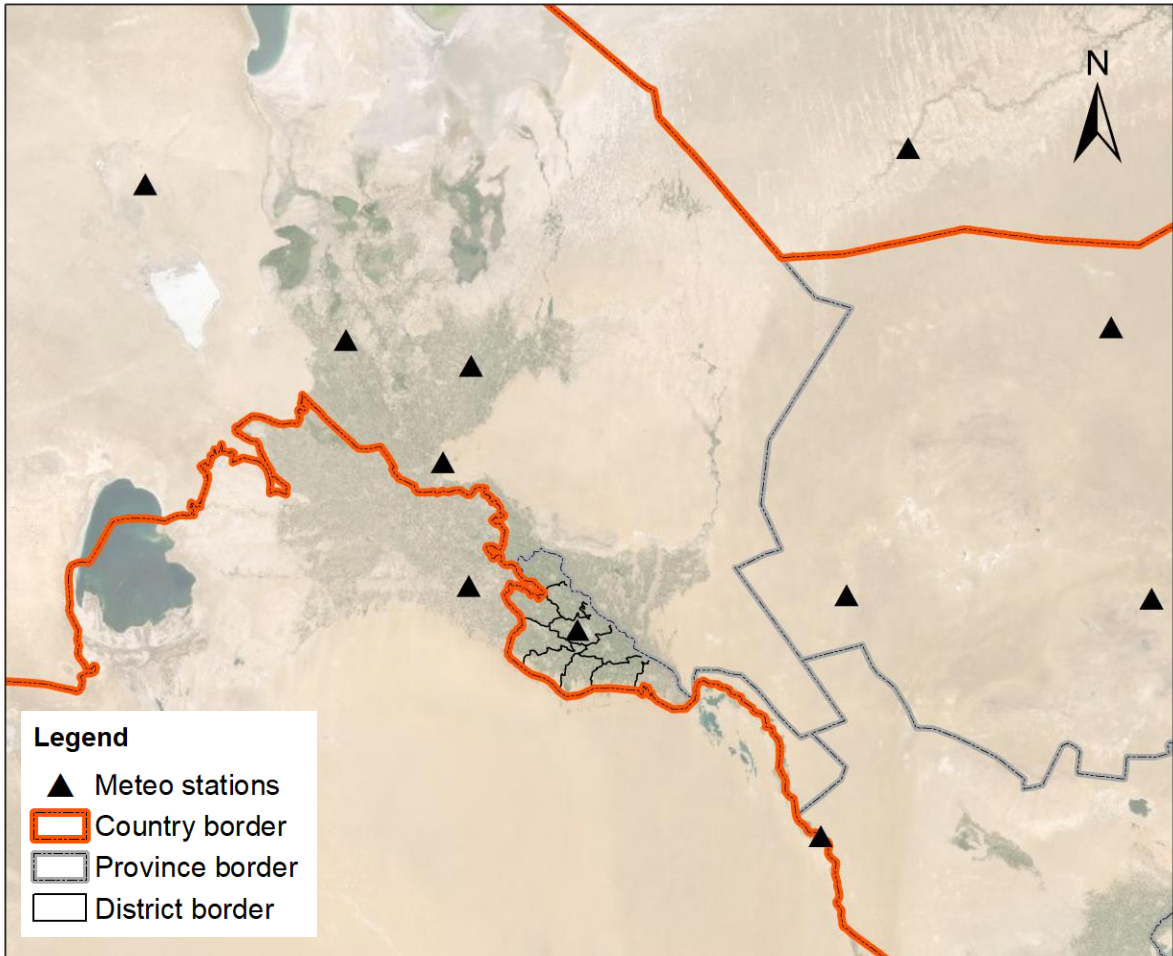
Source: Present and future Köppen-Geiger climate classification maps (Beck et al. 2018).

The climate of the region is sharply continental, with hot and dry summers and cold winters. In winter, the air temperature in Khorezm region is lower by an average of 5° - 8°C than in the rest of the Southern and Eastern part of Uzbekistan.

The average annual temperature is +14.1°C; average temperature in January is -1.0°C, average temperature in July is +29.0°C. The absolute minimum temperature is -32°C, absolute maximum temperature is +45°C. The average annual precipitation in the province is 78-79 mm (mostly in spring and autumn), vegetation period lasts 200-210 days (Kiseliova and Lifshits 1971).

The Köppen-Geiger system classifies climate into five main classes and 30 sub-types. The classification is based on threshold values and seasonality of monthly air temperature and precipitation. Considering vegetation as “crystallized, visible climate”, this classification empirically maps biome distributions around the world: different regions in a similar class share common vegetation characteristics (Beck et al. 2018).

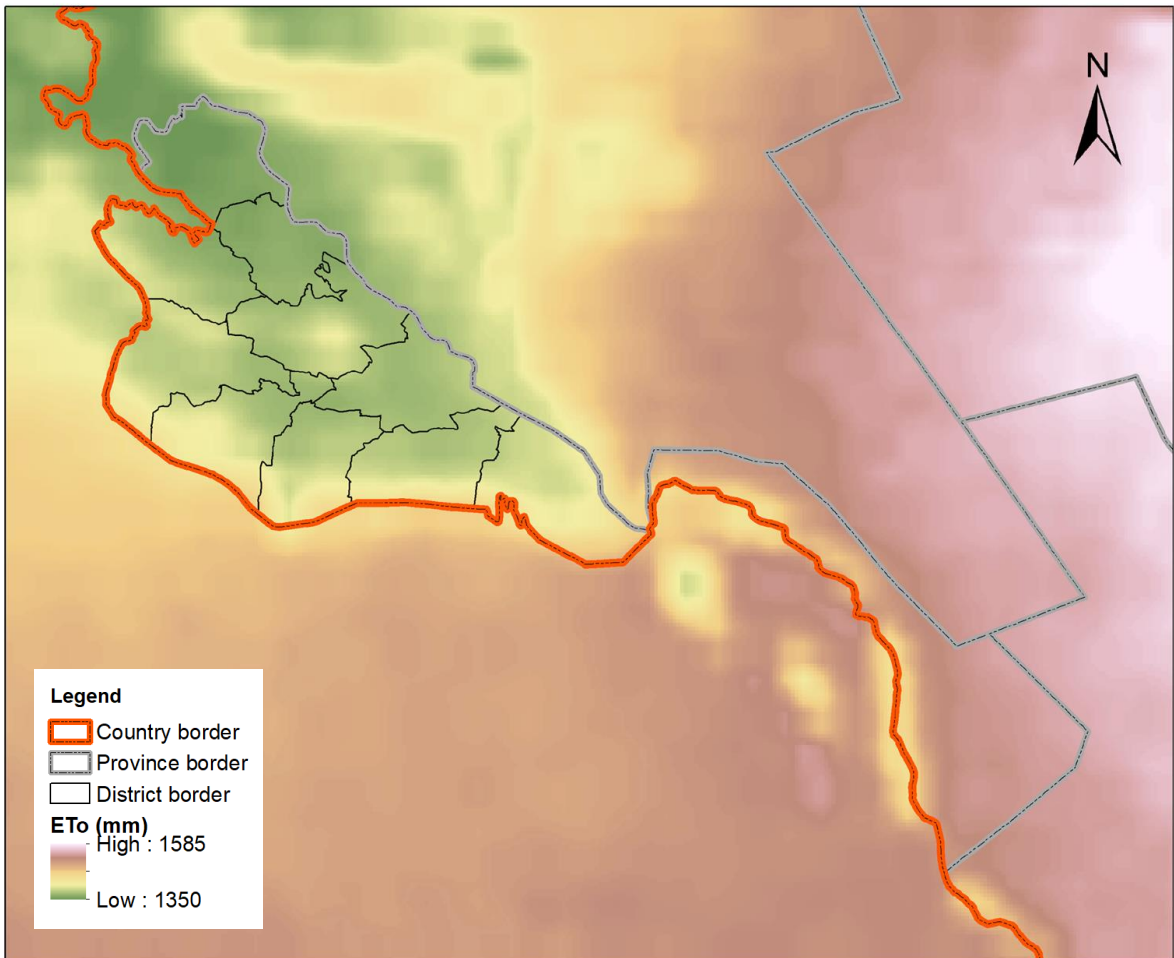
Meteorological stations



The Centre for Hydro-Meteorological Services (Uzhydromet 2022) is a specialized governmental agency vested with tasks, matters, and concerns in the field of hydrometeorology in the Republic of Uzbekistan.

Uzhydromet performs hydro-meteorological and agro-meteorological observations on the entire territory of the Republic of Uzbekistan. The responsibility of Uzhydromet also extends over the stations for long-term observations. The main objectives and tasks of hydrometeorological monitoring are to generate and provide the users with hydrometeorological data, forecasts and analytical information. In our study area we use meteorological data (i.e., precipitation, temperature, solar radiation, relative humidity, wind speed) from 4 weather stations (Chimbai, Jaslyk, Kungrad and Nukus). A wide range of data is necessary to adequately monitor the status of climate and water supply (i.e., precipitation, temperature, stream flow, ground water and reservoir levels, soil moisture, snow pack). These data are often not available at the density required for accurate assessments. Given climate change, seasonal forecasts and warning systems should be also linked with water user and farmer groups as well as extension services for the warnings to be effectively and timely delivered (World Bank 2015).

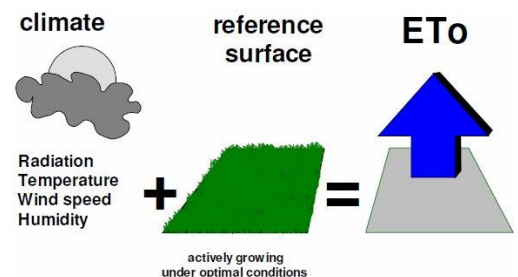
Average annual reference evapotranspiration (ET_o) (1991-2020)



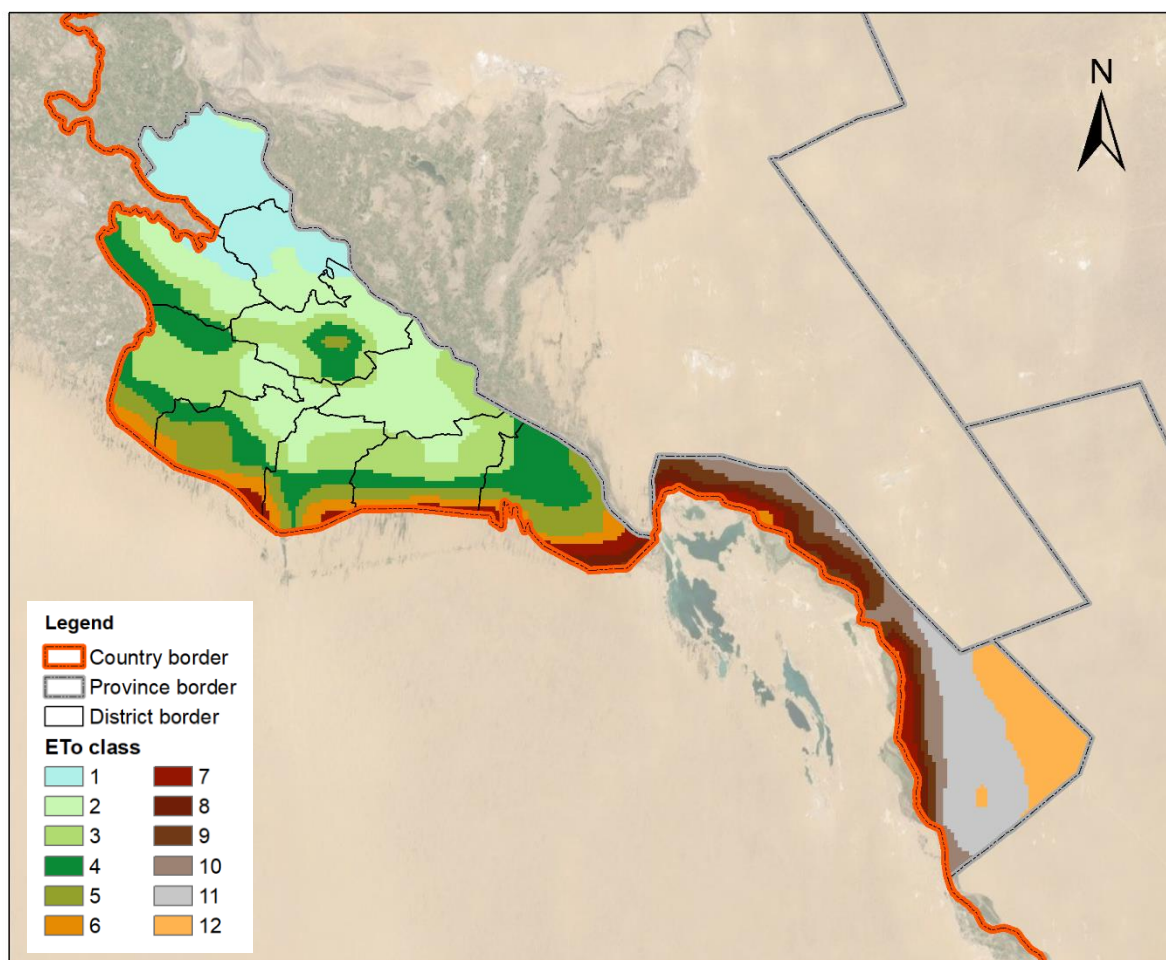
Source: TerraClimate (Abatzoglou et al. 2018).

Reference evapotranspiration (ET_o), is the evapotranspiration rate from a clearly defined reference surface. The concept was introduced to allow the estimation of the evaporative demand of the atmosphere independently of crop type, crop development or management practices. ET_o corresponds to the evapotranspiration from a hypothetical extensive well-watered field covered with 12 cm height green grass having an albedo of 0.23 would experience under the given down-welling short-wave radiation.

TerraClimate is a dataset of monthly climate and climatic water balance for global terrestrial surfaces. It uses climatically aided interpolation, combining high-spatial resolution climatological normals from the WorldClim dataset, with coarser spatial resolution, but time-varying data from CRU Ts4.0 and the Japanese 55-year Reanalysis (JRA55) (Abatzoglou et al. 2018).



Reference evapotranspiration (ET_o) zones (1991-2020)



Monthly Average Reference Evapotranspiration by EToZone (mm/month)

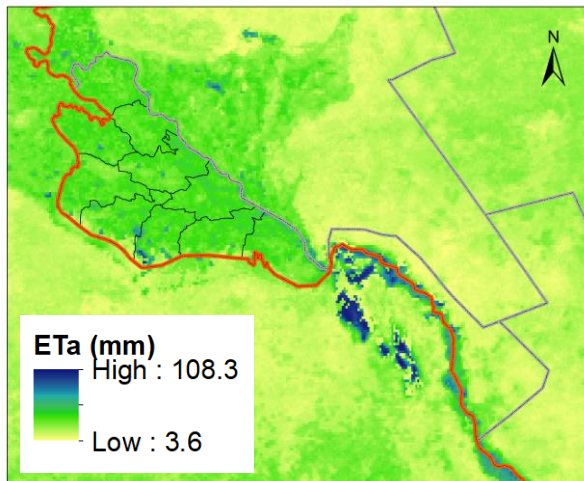
Zone	Area(%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
1	11.7	4.4	17.9	78.6	135	197	236	236	203	138	81.8	30.4	6.6	1365
2	18.4	4.9	19.9	80.7	136	196	236	239	204	140	82.9	31.9	7.1	1378
3	16	5	20.5	81.1	136	197	238	241	205	142	83.8	32.3	7.3	1388
4	12.2	5	20.8	81.4	137	198	239	243	208	143	84.6	32.8	7.5	1400
5	7.2	5.2	21.2	82.4	137	200	242	246	211	145	85.2	33.4	7.4	1415
6	4.2	4.7	21.1	83.3	137	202	244	251	215	148	86.4	33.2	6.8	1433
7	3.7	5.3	22.5	85.5	139	202	244	255	218	151	87.3	36.3	8.9	1454
8	3.6	5.4	22.8	86.8	140	204	245	259	223	155	88.5	37.8	9.5	1476
9	3.6	5.4	22.5	87.7	140	206	247	263	228	158	89.1	37.3	8.8	1493
10	5.3	5.7	23	88.6	140	207	250	266	233	162	90.7	36.9	8.3	1511
11	8.3	5.8	24.3	88.9	140	207	252	267	234	167	95.3	37.5	8.8	1527
12	5.9	6	23.6	88.4	141	207	253	269	235	169	98.2	38.3	9	1537

Source: TerraClimate (Abatzoglou et al. 2018)

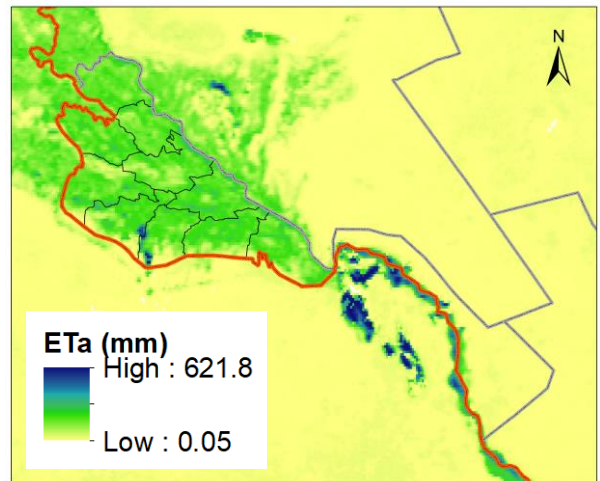
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Average annual actual evapotranspiration (1991-2020)

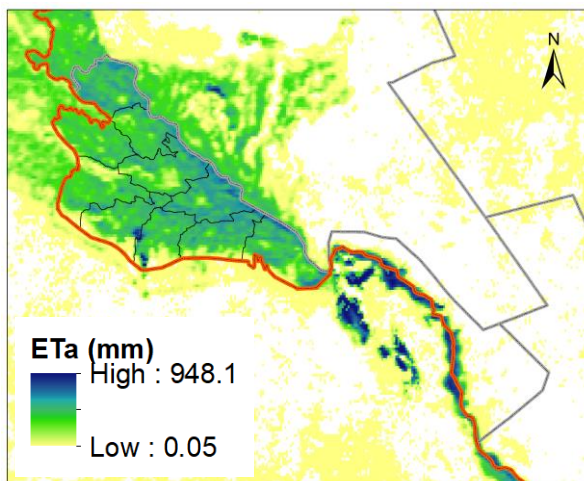
Winter (Dec-Feb)



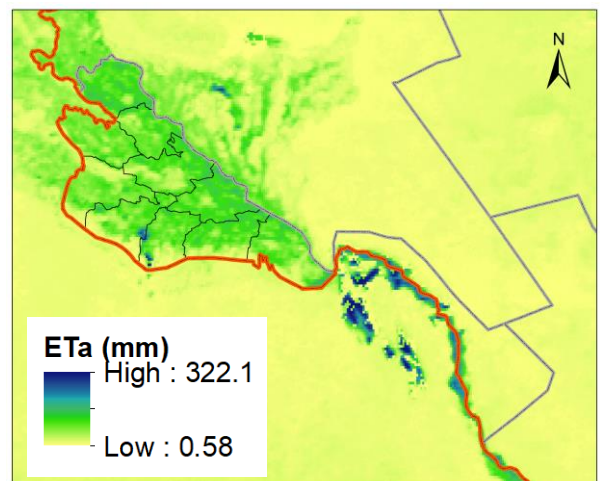
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)



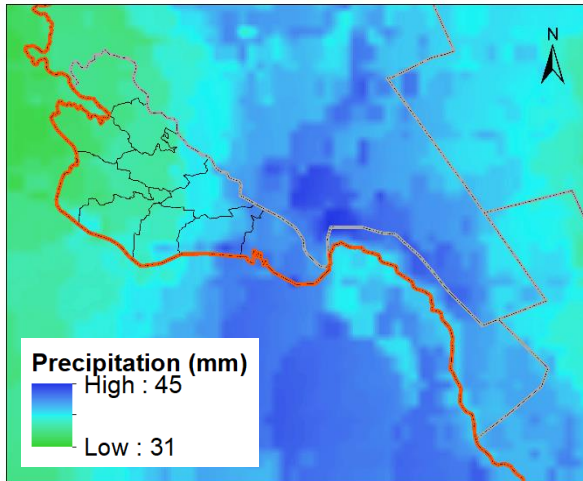
Source: Senay et al. 2020.

Evapotranspiration (ET), for the most part, is the combination of transpiration from vegetation and evaporation from soil surfaces.

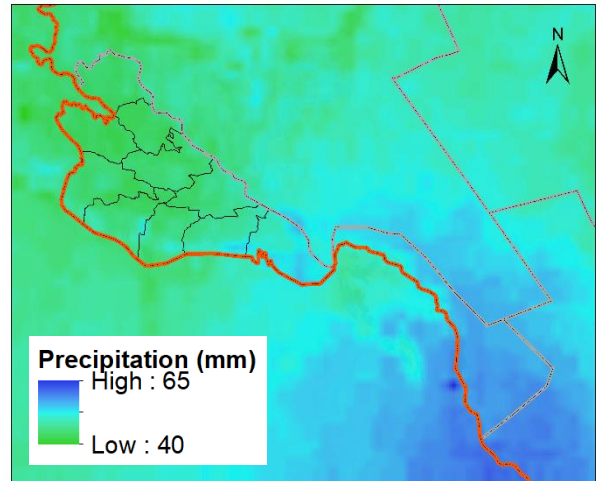
Actual ET (ETa) is produced using the Operational Simplified Surface Energy Balance (SSEBop) model for 2003 to present. The SSEBop setup is based on the Simplified Surface Energy Balance (SSEB) approach with unique parameterization for operational applications. It combines ET fractions generated from remotely sensed Moderate Resolution Imaging Spectroradiometer (MODIS) thermal imagery, acquired every 10 days, with reference ET using a thermal index approach. The unique feature of the SSEBop parameterization is that it uses a pre-defined, seasonally and spatially dynamic surface psychrometer parameter to calculate ET fraction as the difference between observed LST (dry-bulb) and a cold/wet boundary condition (wet-bulb) using the principle of satellite psychrometry (Senay et al. 2020).

Average annual precipitation (1991-2020)

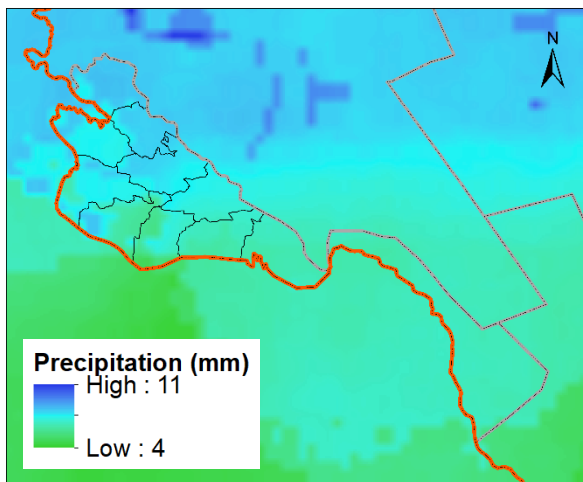
Winter (Dec-Feb)



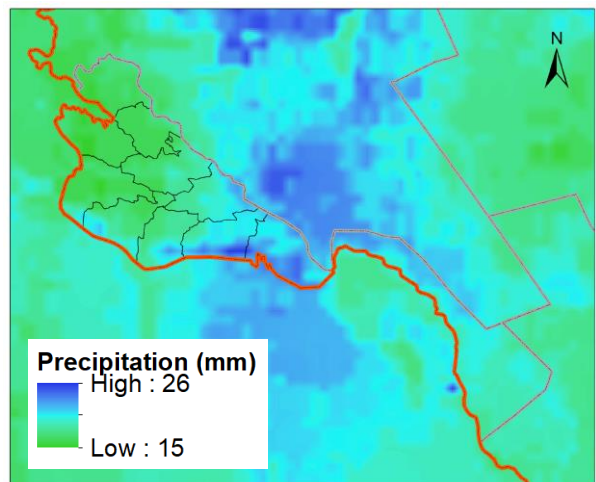
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)

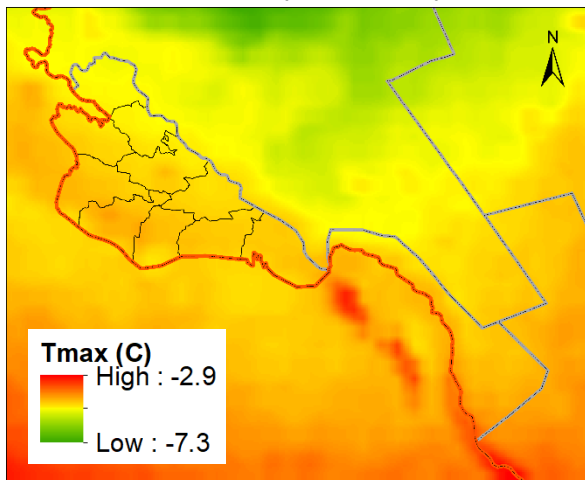


Source: TerraClimate (Abatzoglou et al. 2018).

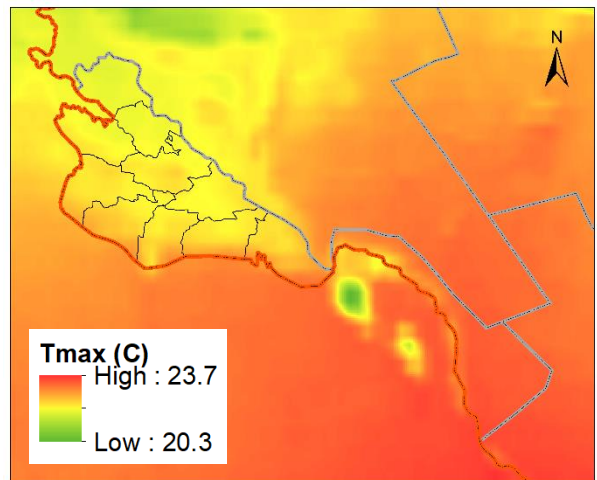
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Average seasonal maximum temperature (1991-2020)

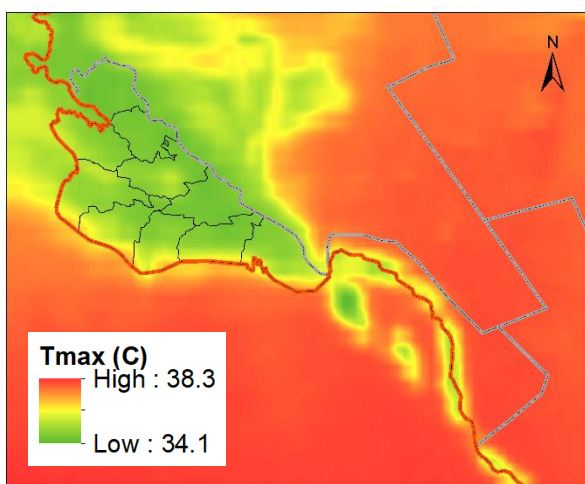
Winter (Dec-Feb)



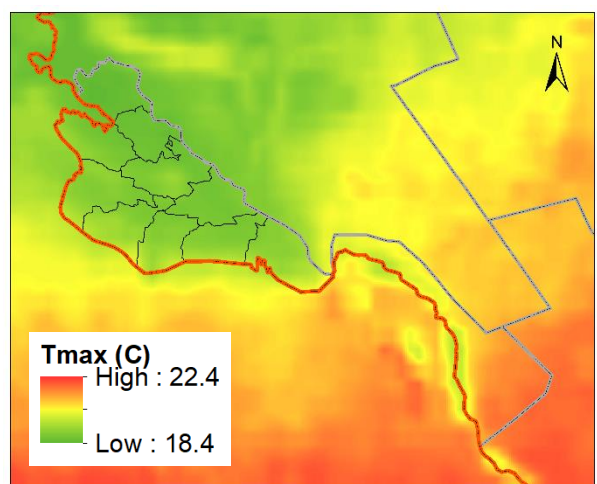
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)

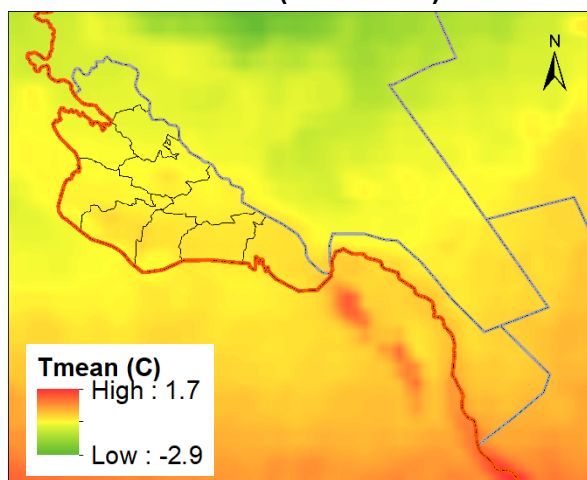


Source: TerraClimate (Abatzoglou et al. 2018).

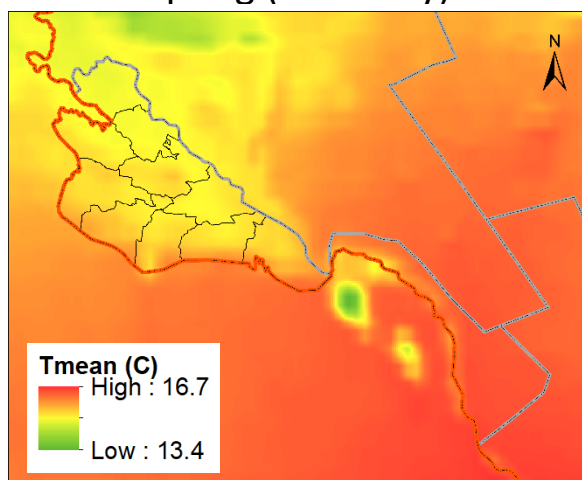
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Average seasonal mean temperature (1991-2020)

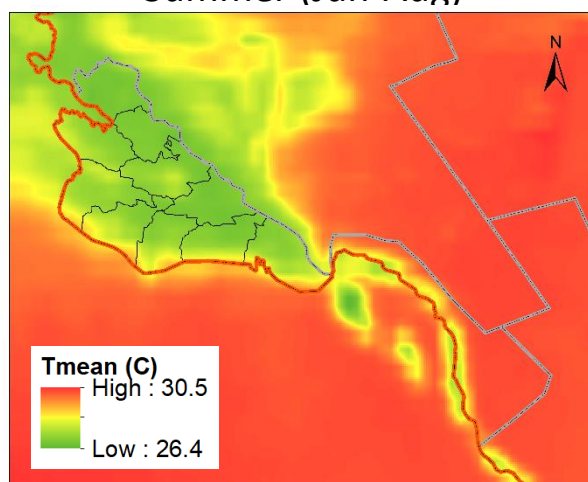
Winter (Dec-Feb)



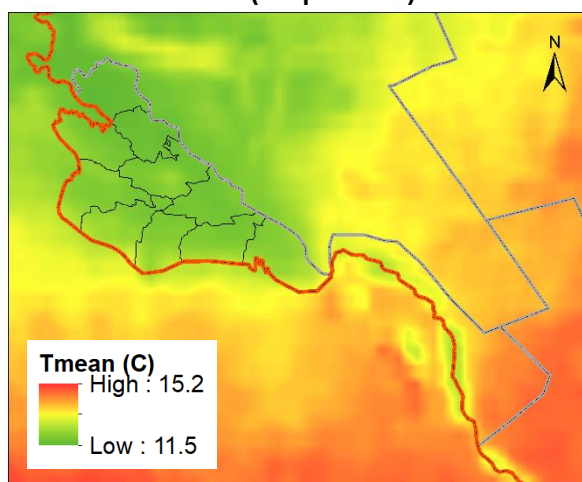
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)

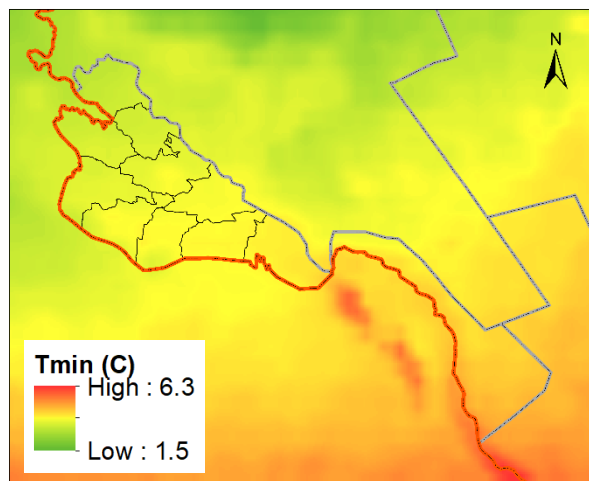


Source: TerraClimate (Abatzoglou et al. 2018).

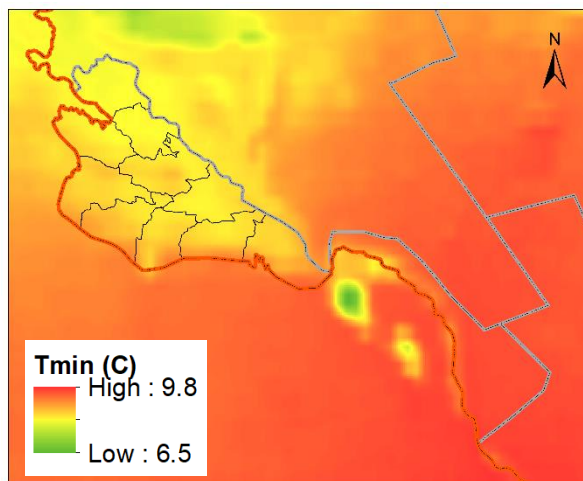
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Average seasonal min temperature (1991-2020)

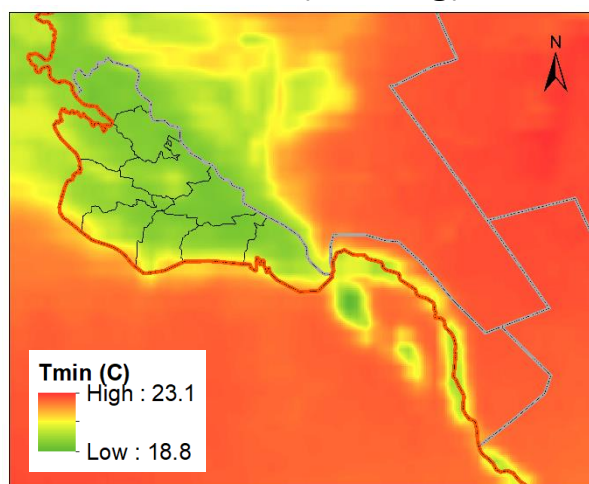
Winter (Dec-Feb)



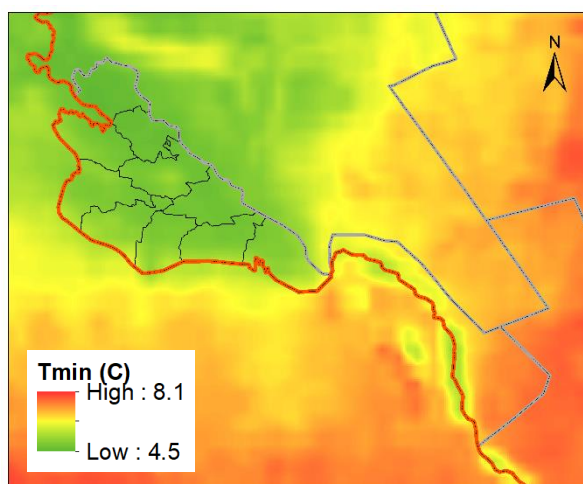
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)

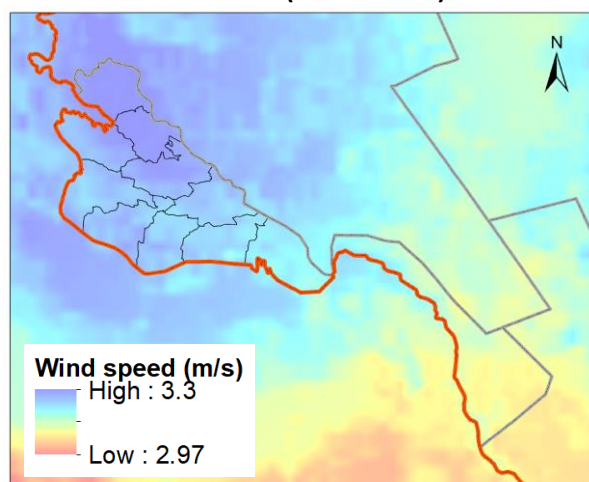


Source: TerraClimate (Abatzoglou et al. 2018).

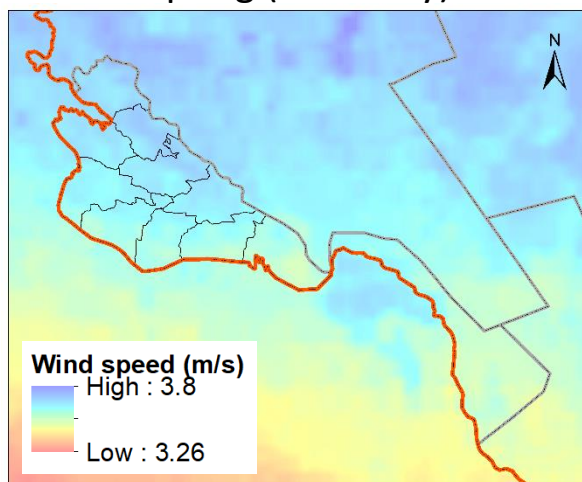
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Average seasonal wind (1991-2020)

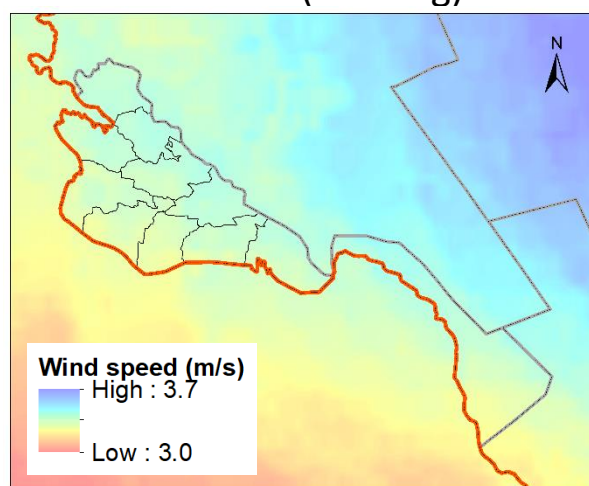
Winter (Dec-Feb)



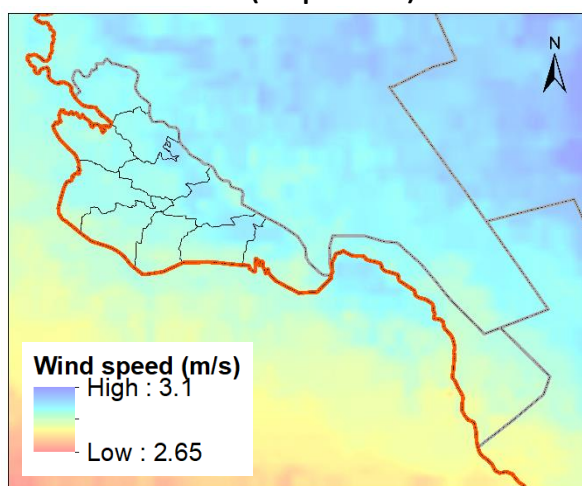
Spring (Mar-May)



Summer (Jun-Aug)



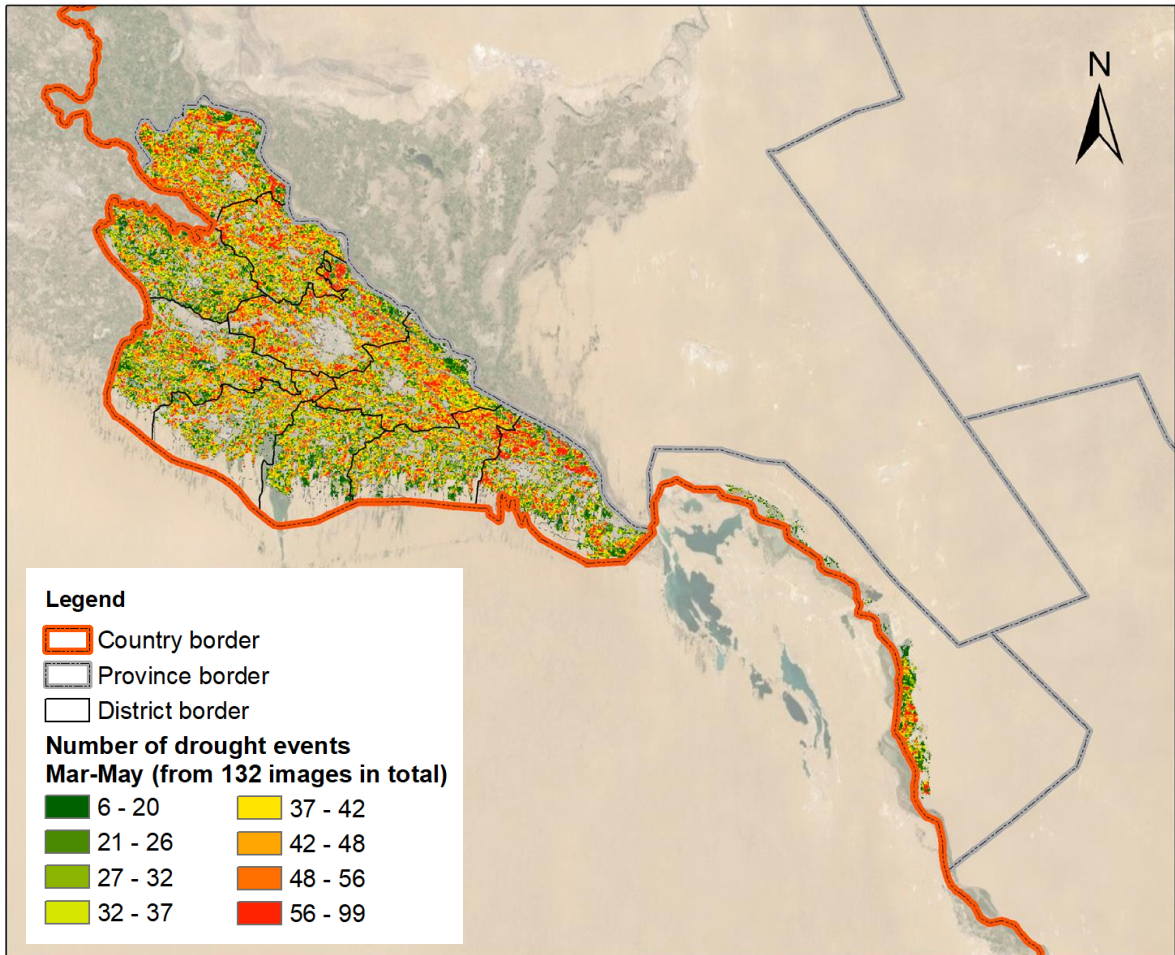
Fall (Sep-Nov)



Source: TerraClimate (Abatzoglou et al. 2018).

TerraClimate is a dataset of monthly climate and climatic water balance for global terrestrial surfaces. It uses climatically aided interpolation, combining high-spatial resolution climatological normals from the WorldClim dataset, with coarser spatial resolution, but time-varying data from CRU Ts4.0 and the Japanese 55-year Reanalysis (JRA55). Conceptually, the procedure applies interpolated time-varying anomalies from CRU Ts4.0/JRA55 to the high-spatial resolution climatology of WorldClim to create a high-spatial resolution dataset that covers a broader temporal record (Abatzoglou et al. 2018).

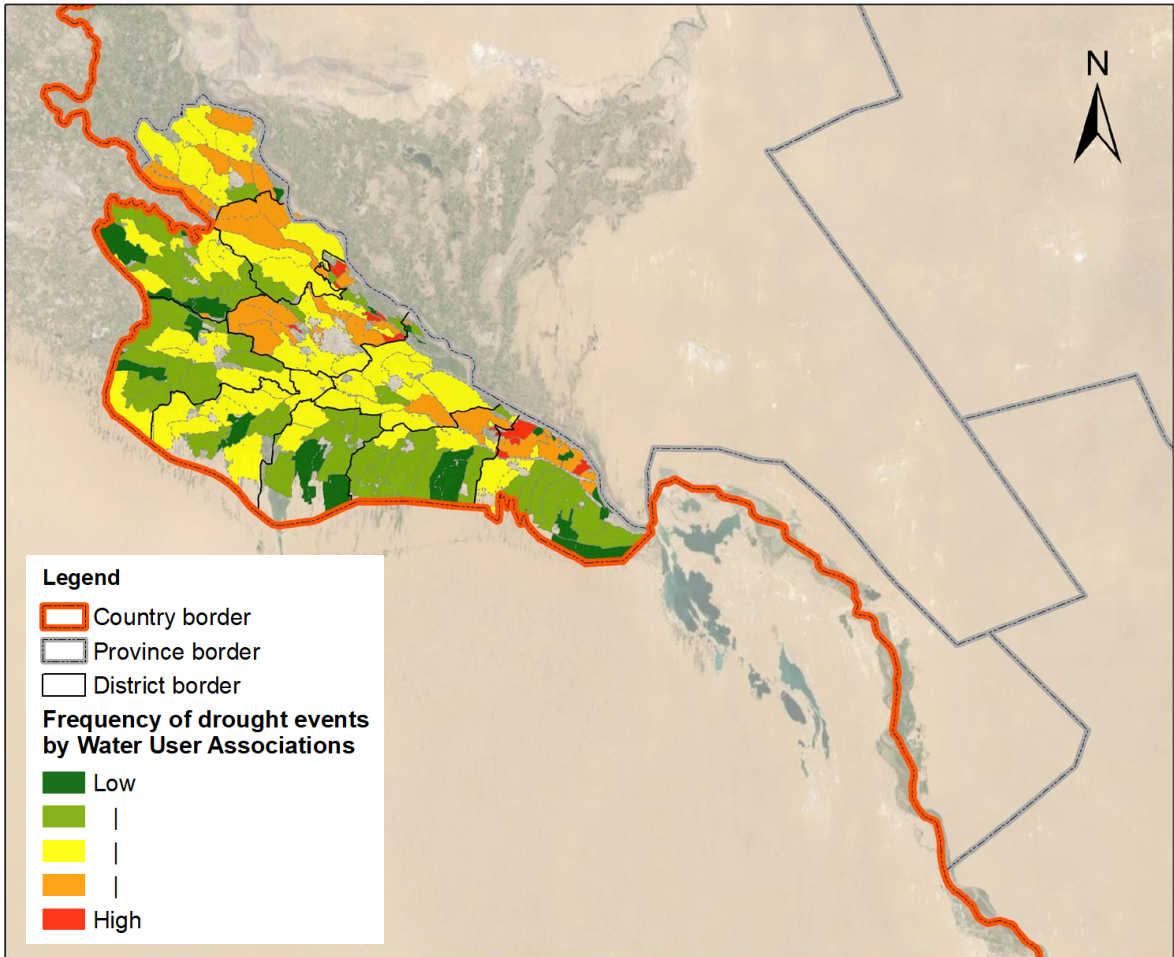
Location of champion farms Winter crops (March-May, 2000-2020)



Drought is a recurring phenomenon that can lead to significant losses to societies affecting different aspects of human life such as agriculture, food security, and the environment. Traditional methods of drought assessment and monitoring rely on rainfall data. However, this approach has two main disadvantages: rainfall data are limited to the region, and they are often inaccurate and difficult to obtain in near-real time. In contrast, satellite-sensor data is continuously available and can be used to detect the onset of a drought, its duration and magnitude. Availability, simplicity, free of charge data, good research literature and citation, minimum requirements of inputs are main criteria, which have been considered to define the methodology.

Kogan (1990) proposed a Vegetation Condition Index (VCI) based on the relative Normalized Difference Vegetation Index (NDVI) change with respect to minimum historical NDVI value. The VCI, therefore compares the current Vegetation Index (VI) such as NDVI or Enhanced Vegetation Index (EVI) to the values observed in the same period in previous years **within a specific pixel**.

Districts with champion farms Winter crops (March-May, 2000-2020)



The VCI is calculated as shown here,

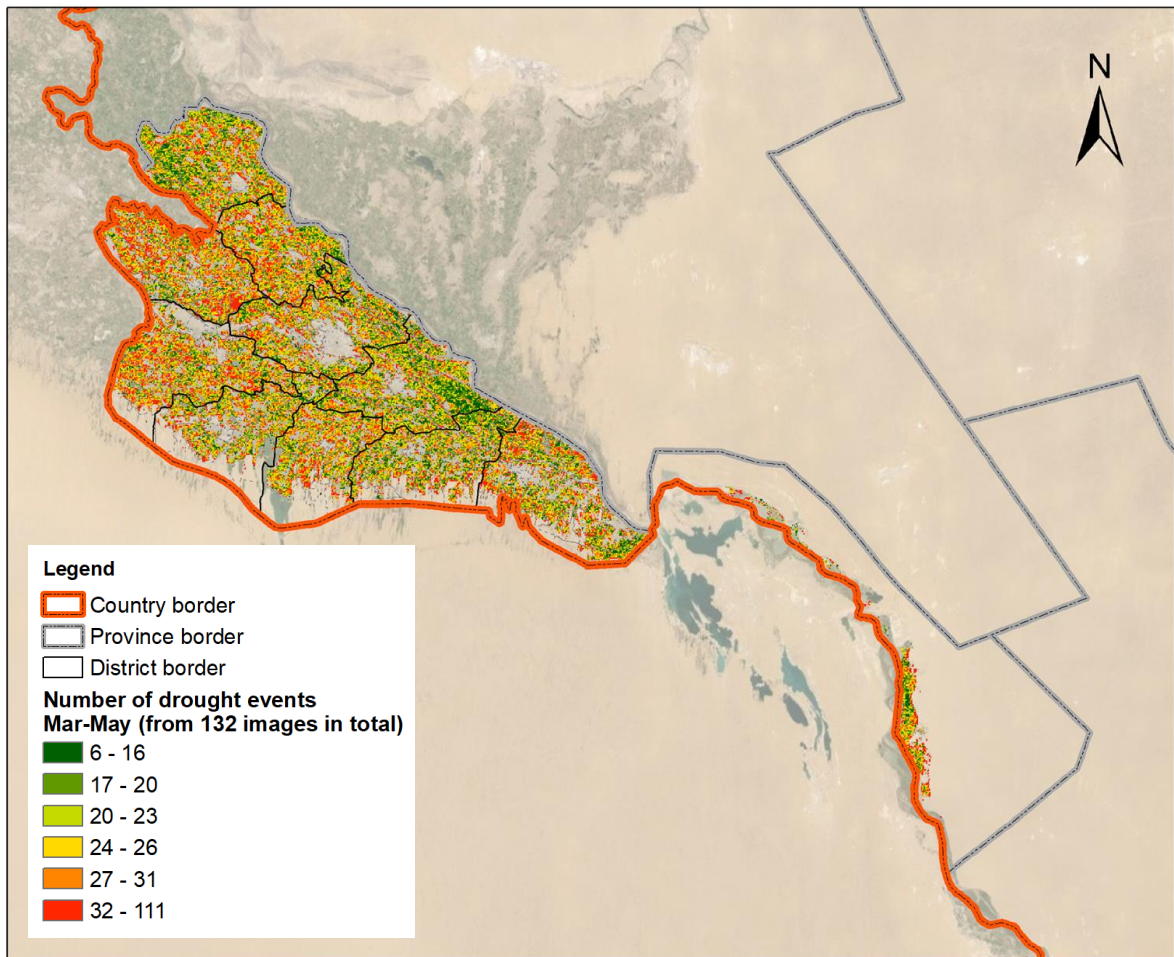
$$VCI_{ijk} = \frac{VI_{ijk} - VI_{i,min}}{VI_{i,max} - VI_{i,min}} * 100$$

where VCI_{ijk} is the VCI value for the pixel i during week/month/DOY j for year k , VI_{ijk} is the weekly/monthly/DOYs VI value for pixel i in week/month/DOY j for year k whereby both the NDVI or EVI can be utilized as VI, $VI_{i,min}$ and $VI_{i,max}$ are the multiyear minimum and maximum VI, respectively, for pixel i .

Consequently, the frequency of Severe Drought cases will be calculated for each pixel in the study area that assist us define the most stable, climate resilient and less vulnerable agricultural lands.

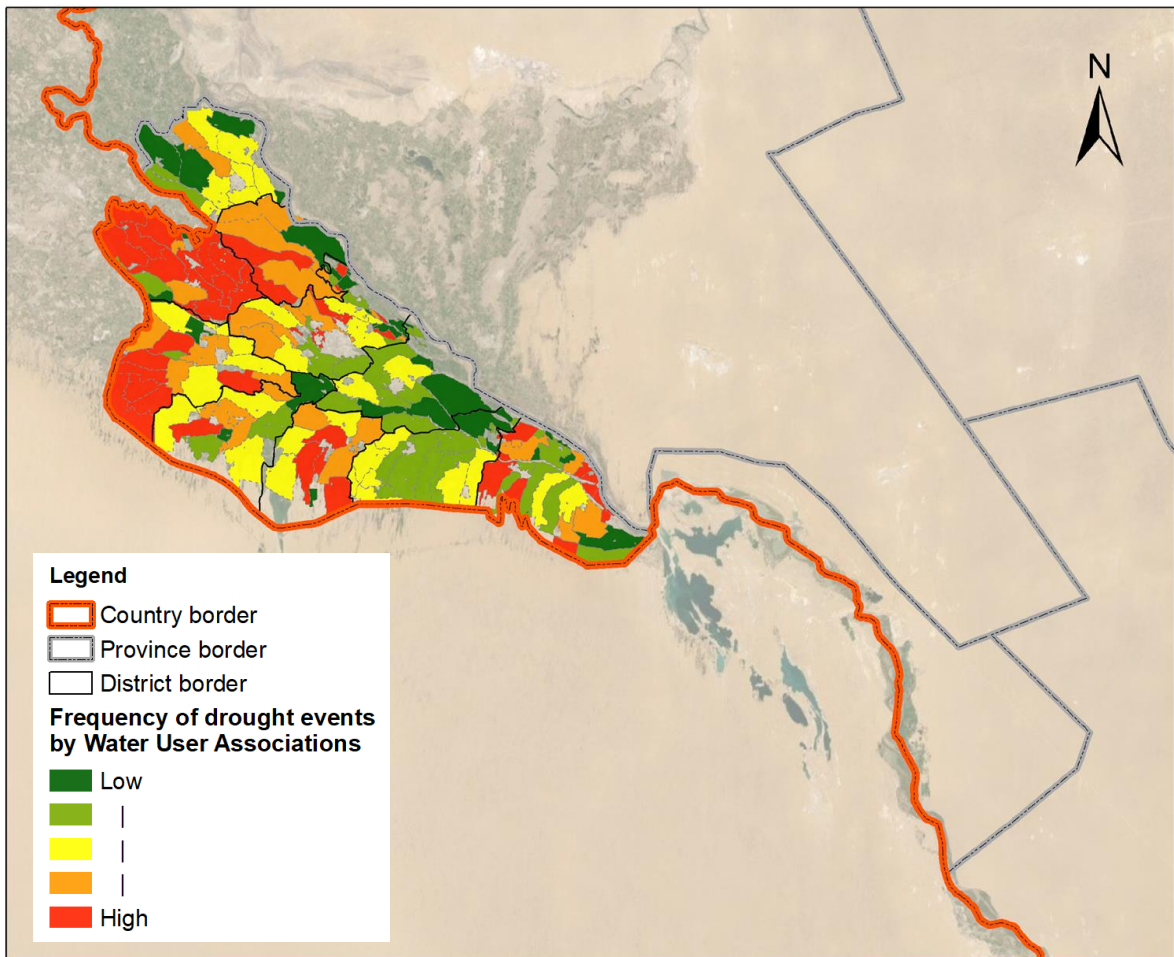
Value	Category
90 - 100 %	No Drought
80 - 90 %	No Drought
70 - 80 %	No Drought
60 - 70 %	No Drought
50 - 60 %	No Drought
40 - 50 %	No Drought
30 - 40 %	Light Drought
20 - 30 %	Moderate Drought
10 - 20 %	Severe Drought
0 - 10 %	Extreme Drought

Location of champion farms Summer crops (June-August, 2000-2020)



Drought is a recurring phenomenon that can lead to significant losses to societies affecting different aspects of human life such as agriculture, food security, and the environment. Traditional methods of drought assessment and monitoring rely on rainfall data. However, this approach has two main disadvantages: rainfall data are limited to the region, and they are often inaccurate and difficult to obtain in near-real time. In contrast, satellite-sensor data is continuously available and can be used to detect the onset of a drought, its duration and magnitude. Availability, simplicity, free of charge data, good research literature and citation, minimum requirements of inputs are main criteria, which have been considered to define the methodology.

Districts with champion farms Summer crops (June-August, 2000-2020)



The VCI is calculated as shown here,

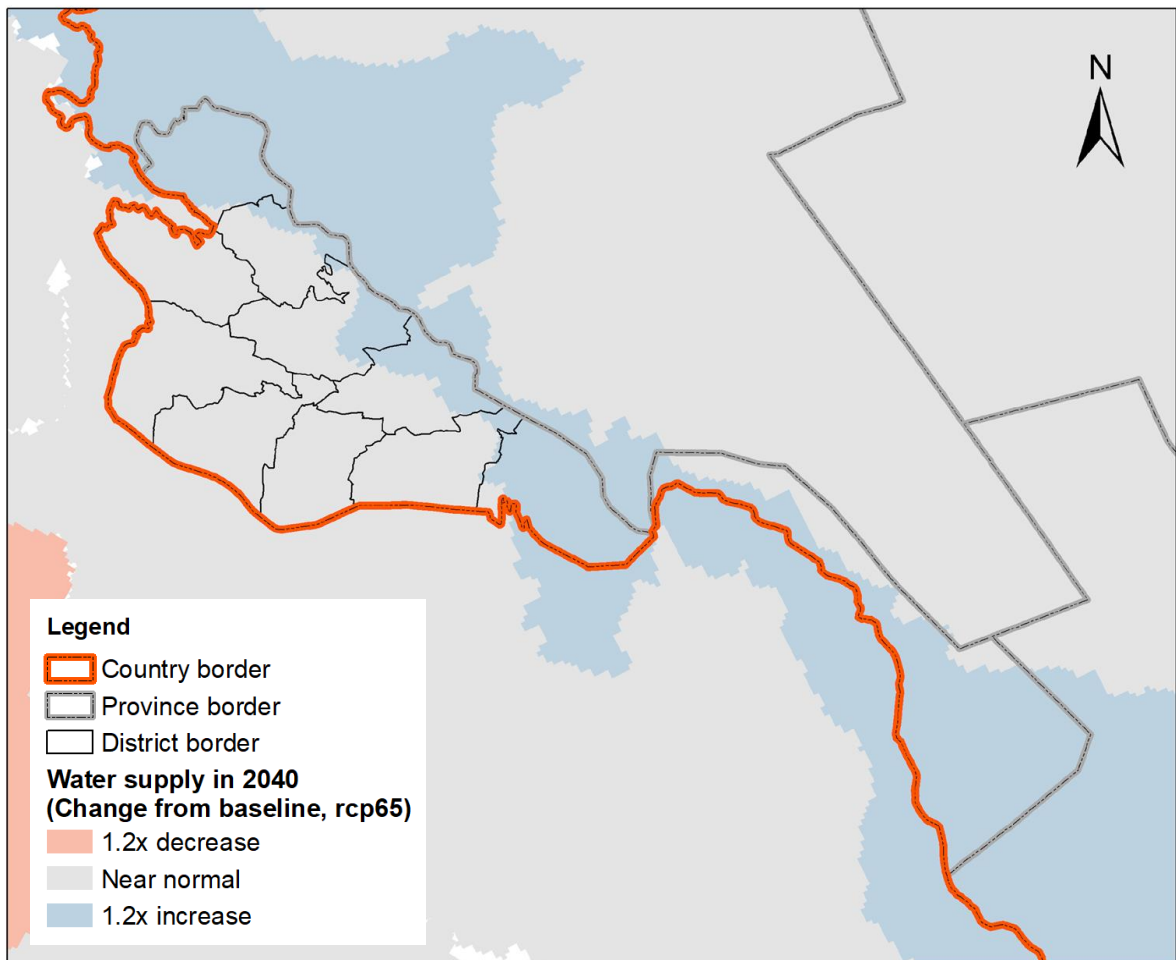
$$VCI_{ijk} = \frac{VI_{ijk} - VI_{i,min}}{VI_{i,max} - VI_{i,min}} * 100$$

where VCI_{ijk} is the VCI value for the pixel i during week/month/DOY j for year k , VI_{ijk} is the weekly/monthly/DOYs VI value for pixel i in week/month/DOY j for year k whereby both the NDVI or EVI can be utilized as VI, $VI_{i,min}$ and $VI_{i,max}$ are the multiyear minimum and maximum VI, respectively, for pixel i .

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40 - 50 %	No Drought
30 - 40 %	Light Drought
20 - 30 %	Moderate Drought
10 - 20 %	Severe Drought
0 - 10 %	Extreme Drought

Water supply in 2040, rcp65

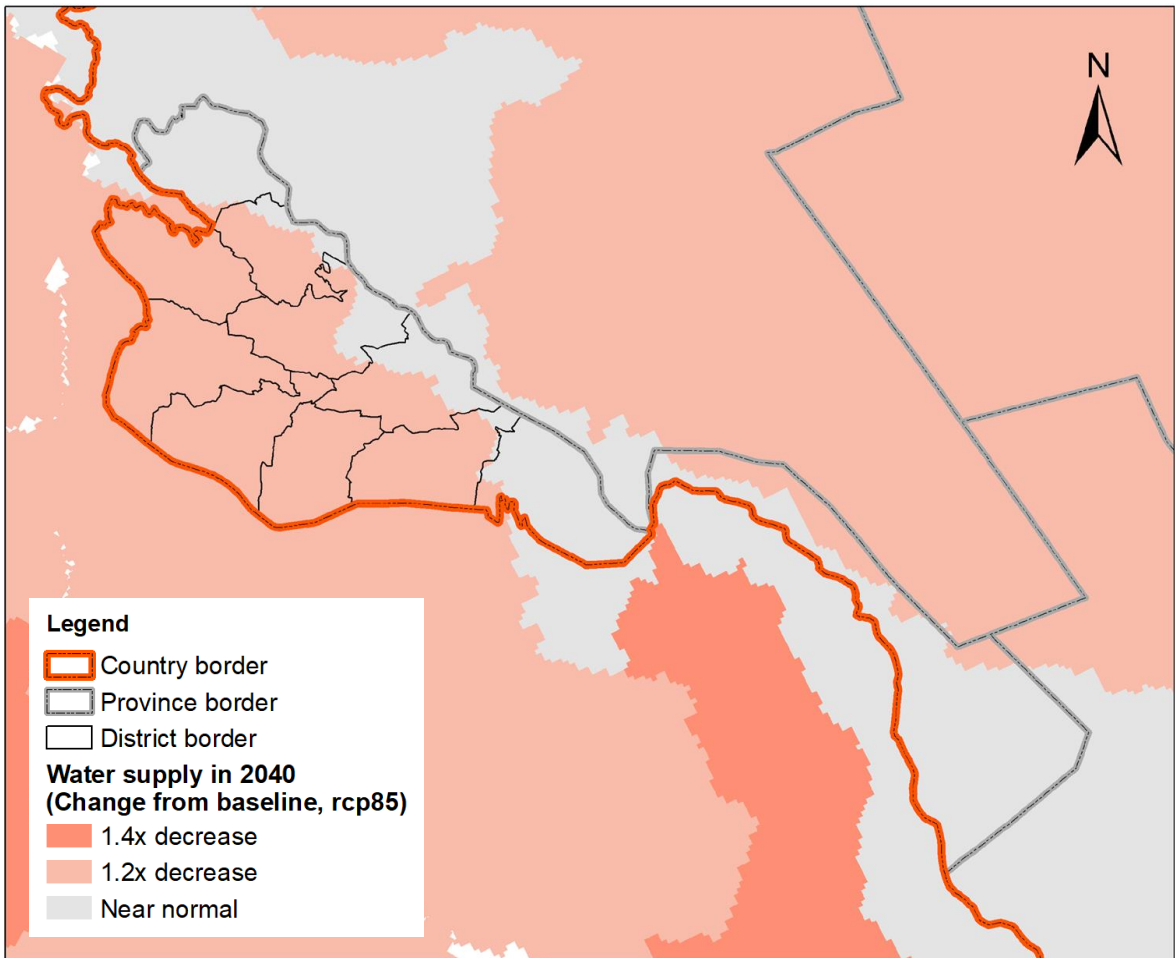


Source: *Aqueduct's tools* (Luck et al. 2015).

Total blue water (renewable surface water) was our indicator of water supply. Projected change in total blue water is equal to the 21-year mean around the target year divided by the baseline period of 1950–2010.

Aqueduct's tools map water risks such as floods, droughts, and stress, using open-source, peer reviewed data. Beyond the tools, the Aqueduct team works one-on-one with companies, governments, and research partners to help advance best practices in water resources management and enable sustainable growth in a water-constrained world (Luck et al. 2015).

Water supply in 2040, rcp85

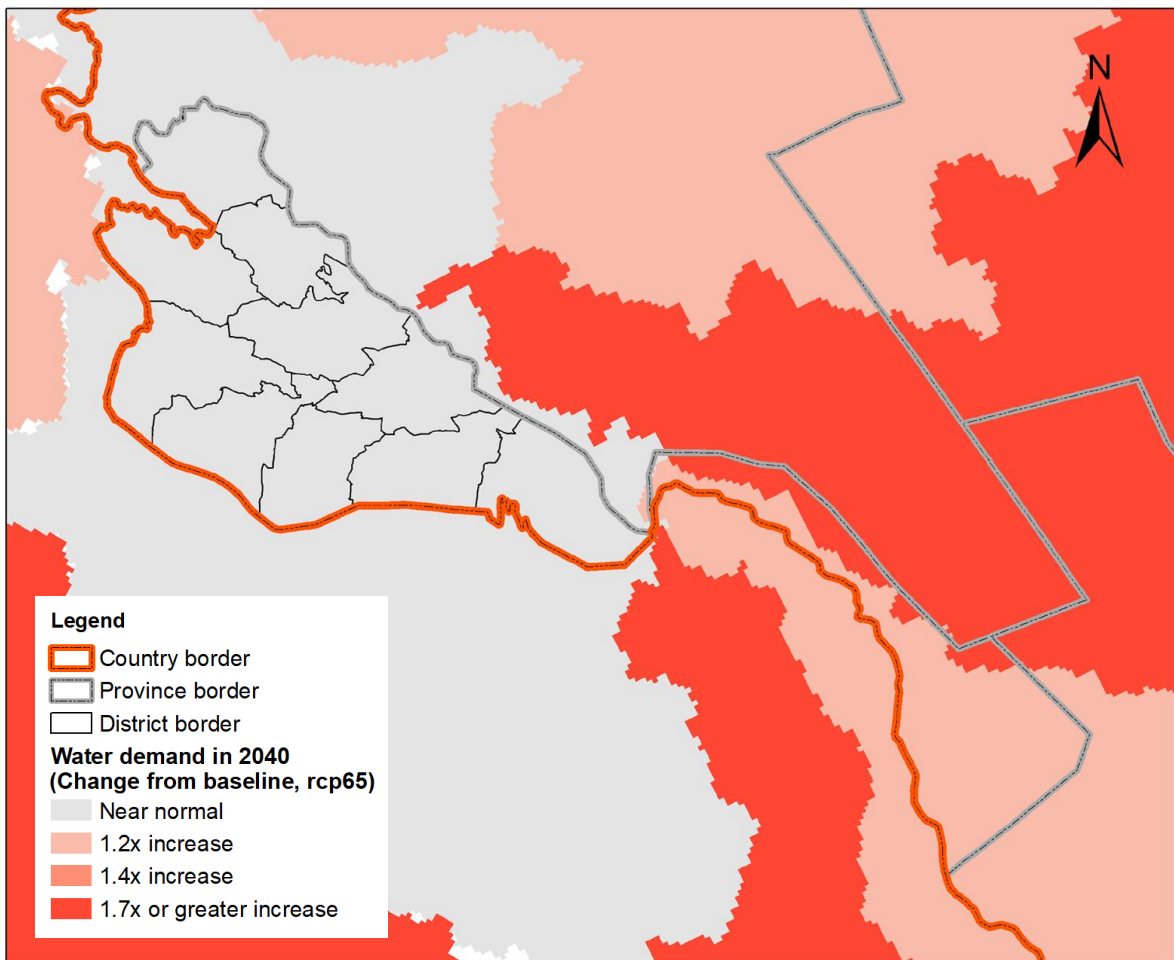


Source: *Aqueduct's tools* (Luck et al. 2015).

Total blue water (renewable surface water) was our indicator of water supply. Projected change in total blue water is equal to the 21-year mean around the target year divided by the baseline period of 1950–2010.

Aqueduct's tools map water risks such as floods, droughts, and stress, using open-source, peer reviewed data. Beyond the tools, the Aqueduct team works one-on-one with companies, governments, and research partners to help advance best practices in water resources management and enable sustainable growth in a water-constrained world (Luck et al. 2015).

Water demand in 2040, rcp65

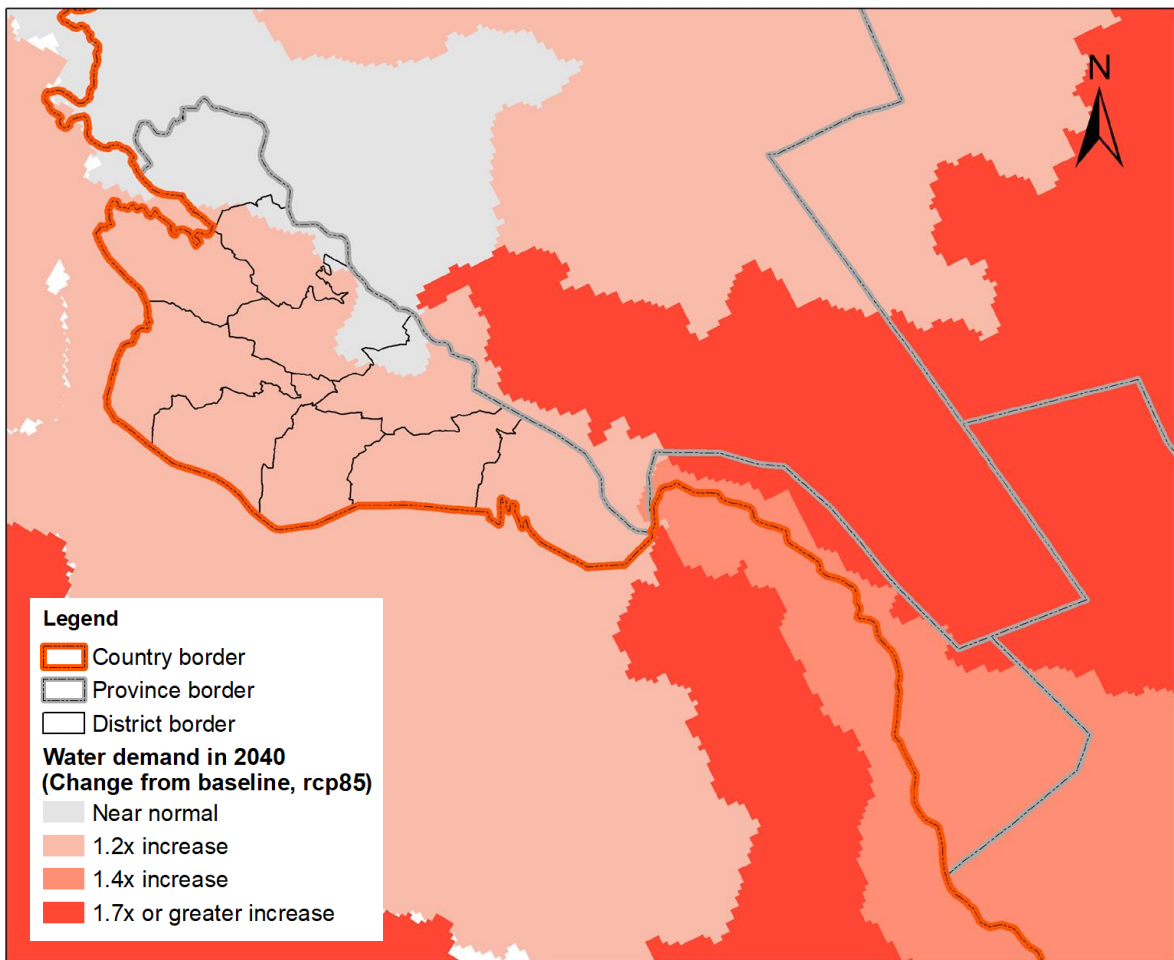


Source: *Aqueduct's tools* (Luck et al. 2015).

Water demand was measured as water withdrawals. Projected change in water withdrawals is equal to the summarized withdrawals for the target year, divided by the baseline year, 2010. Since irrigation consumptive use varies based on climate, we generated unique estimates of consumptive and non-consumptive agricultural withdrawal for each year. Estimates for consumptive and non-consumptive agricultural withdrawal for each ensemble member, scenario, and target year are the mean of the 21-year window around the target year.

Aqueduct's tools map water risks such as floods, droughts, and stress, using open-source, peer reviewed data. Beyond the tools, the Aqueduct team works one-on-one with companies, governments, and research partners to help advance best practices in water resources management and enable sustainable growth in a water-constrained world (Luck et al. 2015).

Water demand in 2040, rcp85



Source: *Aqueduct's tools* (Luck et al. 2015).

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